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AFFORDABLE MILITARY SYSTEMS UTILIZING COMMERCIAL PRACTICES (AMSUCP)

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This technical report has been reviewed and is approved for publication.

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13. ABSTRACT

The study was conducted by a team from Texas Instruments System Group (Lewisville, TX), Lockheed-Martin (Fort Worth, TX),and Computing Devices International (Bloomington, MN). The objective of this study was to 1) evaluate the capability of commercial parts to operate over the temperature range required in avionics environments, and 2) to evaluate the true environments to which electronic parts are subjected in different avionics applications.

This report examines the extended temperature capabilities of today's plastic encapsulated microcircuits (PEMs) and a specific military avionics systems life cycle profiles. Several studies were conducted to assess a small sample of PEMs for their extended temperature capabilities and performance after 2-12 years of field-storage in various environments. Comparison of 3 PEM CCAs (circuit card assemblies) and 3 MIL-IC CCAs was also made after subjecting them to standard assembly processes and limited environmental evaluations.

Results of these studies support the use of best commercial practices including today's PEMs in military applications. Effective system application and component capability match are key to delivery of reliable military systems at the lowest possible cost. This report delineates a framework for PEM implementation and system reliability focus whether military or commercial components are used.

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TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Renewed interest in the use of commercial parts for extended-temperature applications led Wright Laboratory, Manufacturing Technology Directorate to commission a study to evaluate the feasibility of commercial parts in avionics environments. The study was conducted by a team from Texas Instruments System Group (Lewisville, Texas), Lockheed-Martin (Fort Worth, Texas) and Computing Devices International (Bloomington, Minnesota). The objective of this study was twofold: (1) to evaluate the capability of commercial parts to operate over the temperature range required in avionics environments, and (2) to evaluate the true environments to which electronic parts are subjected in different avionics applications.

This paper examines the extended-temperature capabilities of today's plastic encapsulated microcircuits (PEMs) and life cycle profiles of a specific military avionics system. Several studies were conducted to assess a small sample of PEMs for their extended temperature capabilities and performance after 2-1/2 years of field storage in various environments. Comparison of three PEM circuit card assemblies (CCAs) and three Military integrated circuit (Mil IC) CCAs is also made after subjecting them to standard assembly processes and limited environmental evaluations.

Results of these studies support the use of best commercial practices including today's PEMs in military applications. Effective system application and component capability match are key to delivery of reliable military systems at the lowest possible cost. This paper delineates a framework for PEM implementation and system reliability focus whether military or commercial components are used.

APPROACH

To fulfill the program objectives as they were specified in the Abstract, the following approaches are exercised:

- Demonstrate today's PEM extended temperature capabilities through 3 experimental evaluations
- Explore aircraft's inflight temperature environments via an independent worst-case temperature study on world-wide USAF bases
- Quantify the avionics application reality and feasibility of using PEMs
- Review the significance of system reliability focus to optimize savings in total product cost
- Propose a PEM Implementation framework to leverage Best Commercial Practices (BCP) effectively for utilizing PEMs in today's military programs.

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ACRONYMS AND ABBREVIATIONS

6-DOF	Six Degrees Of Freedom
ACC	Air Combat Command
AFCCC	Air Force Combat Climatology Center
AIBU	Advanced Interference Blanker Unit
AMSUCP	Affordable Military Systems Utilizing Commercial Practices
AOQ	Average Outgoing Quality
ARWR	Advanced Radar Warning Receiver
ASPJ	Airborne Selft Protection Jammer+B24
BCP	Best Commercial Practices
BGA	Ball Grid Array
C-SAM	"C" Mode Scanning Acoustical Microscope
CADC	Central Air Data Computer
CCA	Circuit Card Assembly
CMDS	Countermeasures Dispenser Set
CMOS	Ceramic Metal-Oxide Semiconductor
C_{PK}	Process Capability Index
CSFDR	Crash Survivable Flight Data Recorder
CTF	Contractor Test Facility
DFLCS	Digital Flight Control System
DHTL	Dynamic High Temperature Life Test
DIP	Dual Inline Package
DoD	Department of Defense
DPA	Destructive Physical Analysis
DRAM	Dynamic Random Access Memory
DS&E	Defense Systems & Electronics (TI)
DTE	Date Transfer Electronics
ECM	Electronic Countermeasures
ECS	Environmental Control System
ECU	Environmental Control Unit
ENG	Engine
EOS	Electrical Over Stress
ESD	Electrostatic Discharge
ESS	Environmental Stress Screening
EW	Electronic Warfare
FCC	Fire Control Computer
FCR	Fire Control Radar
FLCS	Flight Controls System
GFE	Government Furnished Equipment
GPS	Global Positioning System
HALT	Highly Accelerated Life Test
HARM	High Speed Antiradiation Missile
HAST	Highly Accelerated Stress Test
HTOL	High Temperature Operating Life Test
HTS	HARM Targeting System
HTSL	High Temperature Storage Life
HTSSLT	High Temperature Steady State Life Test

HUD	Head Up Display
IBU	Interference Blanker Unit
IC	Integrated Circuit
IDM	Improved Data Modem
Ind	Industrial
INS	Inertial Navigation System
JAN	Joint Army/Navy
LANTIRN	Low Altitude Navigation and Targeting Infrared for Night
LHP	Left Hard Point
LMTAS	Lockheed Martin Tactical Aircraft Systems
LRU	Line Replaceable Unit
LTOL	Low Temperature Operating Life
MCM	Multi-Chip Modules
MESL	Minimum Essential Subsystems List
MFD	Multifunction Display
MFDS	Multifunction Display Set
Mil-Spec	Military Specification
N/A	Not Applicable
NCMS	National Center for Manufacturing Sciences
OEM	Original Equipment Manufacturer
OES	Original Equipment Supplier
PCB	Printed Circuit Board
PCT	Pressure Cooker Test
PDIP	Plastic Dual-In-Line Packages
PEM	Plastic Encapsulated Microcircuit
PIND	Particle Impact Noise Detection
PSI	Pounds per Square Inch
QML	Qualified Manufacturers List
RDR ALT	Radar Altimeter
RF	Radio Frequency
RHP	Right Hard Point
RIU	Radar Interface Unit
RLG	Ring Laser Gyro
RMS	Root Mean Square
RWR	Radar Warning Receiver
SCD	Source Control Drawings
SMD	Standard Military Drawings
SMS	Stores Management Set
SMT	Surface Mount Technology
SOIC	Small Outline Integrated Circuit
SPC	Statitistical Process Control
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TH	Thru-hole
THB	Temperature Humidity Bias
TSHK	Thermal Shock
UFC	Up Front Controls
USAF	United States Air Force
VP	Video Processor
WL	Wright Laboratories

SECTION 1
INTRODUCTION

In recent years, DoD leadership in commercializing military systems cultivated an innovative and competitive spirit among all stakeholders in today's military businesses. Such transformation initiated with the Perry directive that began the focus of utilizing the best commercial practices—rather than the traditional high-cost and inspection-oriented military process—to achieve the ultimate affordability goal. To meet this new challenge, each specific military application and applicable commercial practices must be explored fully to eliminate any possible arbitrary and conservative specifications.

A resurgence of recent commercialization studies demonstrated that today's PEMs offered by best-in-class commercial suppliers could provide the optimum cost solution for building affordable and reliable modern military systems. This paper focuses on the extended-temperature capabilities of PEMs and the realistic environments in today's F-16 avionics application.

SECTION 2
PEM ASSESSMENT

This section begins with the basic understanding of BCP and reasons for focusing on PEMs (non-military ICs) in this study. The following paragraphs assess today's integrated circuit (IC) technology, packaging, and obsolescence trends, which have become the key issues in today's commercialization thrust. As part of the overall PEM assessment process, the perceived concerns and considerations to mitigate these concerns are addressed. Three separate PEM experimental evaluations have been conducted at Texas Instruments (TI) to assess extended temperature capabilities of PEMs. The results of these evaluations are the major part of this section.

2.1 BASELINE EVALUATIONS: WHY PEMS?

An important aspect of the conversion from Military Specification (Mil-Spec) components to commercial components is the overall methodology for determining which commercial parts are suitable in specific applications and how to ensure the consistency of the quality of these parts for production use. The adoption of BCP does not advocate blanket usage of all commercially available parts. A systematic process for assessing these parts and their suitability for use in the required environment is essential. This will reduce risk significantly and ensure the essential design considerations are evaluated before a decision is made.

The use of BCP has been identified as a potential for reducing the costs of military systems. A military contractor can pursue commercial practices that provide cost savings by the refinement and standardization of shop processes, removal of non-value added processing, and the correct identification of true performance requirements. The focus of this section is toward components that can account for 15 to 85 percent of the electronic component procurement costs.

2.1.1 Cost Impacts of Microcircuits (ICs)

To reduce the cost of electronics, the focus is often directed toward the procurement cost of materials. An insight into the impact of using non-military-compliant commodity components is provided in **Table 2-1**.

Table 2-1 highlights the differences between existing military components and non-military equivalent devices; for example, there are significant cost advantages in using non-military resistors and capacitors. The overall market impact of these commodities (as well as all the others listed) is dwarfed by the potential impact from microcircuits alone. Frost & Sullivan (Mountain View, California)[1] reported that the worldwide market for resistors in 1995 was estimated to be $2.48 billion, growing to $4.12 billion by the year 2002. During this time period however, the military portion of this market is expected to shrink.

While resistors and capacitors are among the highest volume commodities in the electronics market, the material cost for standard commodity parts are often driven by the cost of microcircuits. In contrast, Dataquest reported the worldwide semiconductor market to be $110 billion in 1994 and $154 billion in 1995. In 1995, the digital microcircuit market alone had accounted for approximately $100 billion. Although the 1996 market was down slightly (driven mostly by DRAM memory pricing declines), the overall semiconductor market is predicted to continue to grow during the next 10 years. When attempting to lower component costs, reducing the cost of microcircuits in military electronics is like picking the lowest hanging fruit.

Table 2-1. Non-Military Components Matrix

Non-Military Components Matrix						
	Available Temperature Range	**Approximate Price Savings**	**Size/Other Weight/Savings**	**Reliability Environmental Concerns**	**Suppliers/Delivery**	**Comments**
Capacitors	-55 to +125°C	50% (in volume)	Smaller package sizes available. Extended capacity ranges	Approaches military, no burn-in available	Use recommended suppliers; higher minimum buys	Only applies to SMT parts; no appreciable savings in converting thru-hole to commercial
Resistors	-55 to +125°C	50% (in volume)	Some extended resistance values	Approaches military, no burn-in available	Use recommended suppliers; higher minimum buys	Only applies to SMT parts; no appreciable savings in converting thru-hole to commercial
Hardware (nuts, bolts, screws, etc.)	Depends on materials and finishes	Depends on quantity and availability	N/A	Depends on part type. In general less testing, less environmental resistance for plated products, and fewer performance requirements.	Use recommended suppliers/less lead time (depending on part type)	
Connectors	-55 to +105°C	-50% to +50%		Temperature range limited mechanical integrity by use of plastic components	Use recommended suppliers	
Electro Mechanical Devices	-45 to +85°C	Delay lines (80%) Transformers (50%) Relays (80%) Coils (50%)	Commercial part may perform better due to use of leading edge parts in construction—smaller	Commercial part may perform better and be more reliable	Broader base of suppliers. Lead times are typically 1/4 of military parts.	
Discretes (Diode/Transistor)	-55 or -65°C to +125 to >+200°C	50 to 95%	None unless plastic used	Little reliability data on plastic. Information here is for hermetic	Higher minimum buys in commercial/ most buys would be through distribution; typically short delivery.	Only applies to SMT parts; no appreciable savings in converting thru-hole to comical
Digital ICs	0 to + 70°C; limited supply of -40 to +85°C	20 to 80%	Smaller for high pin count (tighter pitch)	98% plastic. Limited temperature range. Potential for infant mortality (limited/no burn-in)	Most likely serviced by distribution only; not all suppliers manufacture with equal quality	May be available in alternate temperature ranges, although standards are non-existent
Linear ICs	0 to +70°C; limited supply of -40 to +85°C	20 to 80%	Smaller package sizes available	70% plastic. Limited temperature range. Potential for infant mortality (limited/no burn-in)	Most likely serviced by distribution only; not all suppliers manufacture with equal quality	Hybrid parts are mostly full military qualified; limited plastic SMT package availability for high current devices

The military microcircuit market is following the same trends as the resistor market. During the early years of semiconductors, the military market was a significant market driver. The computer, telecom, and consumer markets have since fueled the explosive growth rate of the semiconductor market during the 1980s and 1990s. Because of the overall industry growth, the $1 billion military market currently accounts for less than 1 percent of the worldwide semiconductor market.

2.1.2 Why Use PEMs for Military Applications?

To remain competitive in today's semiconductor market, manufacturers have been required to install expensive new processing facilities. The price of a single new semiconductor facility is equivalent to the entire sales of military microcircuits during a single year (approximately $1 billion). While many military systems designs can be achieved with existing technology—and take advantage of the processing improvements and the advanced technology associated with it—it is imperative that military users leverage off of the semiconductor market drivers.

The majority of non-military microcircuits[(2)] are offered in plastic packaging (PEM),[(3)] while the majority of military-compliant microcircuits[(4)] are offered in hermetically sealed packages. The major reasons for the lower component cost for a PEM versus a hermetically sealed (i.e., ceramic, metal, etc.) microcircuit are based on higher volume, highly automated processing, raw material costs, and the reduction of non-value added testing.

Use of non-military microcircuits improves the availability of newer technology. Newer technologies can provide newer product functions (e.g., improved system performance) and improved board-level packaging density (i.e., space and weight savings).

Cost savings is often cited as the major reason to consider the use of non-military microcircuits. Advantages of using non-military microcircuits includes:

- Lower price
- Lower weight
- High pin count devices are available in smaller packages
- More opportunity for process refinements because PEMs are manufactured in higher volumes
- Greater availability of state-of-the-art functionality
- Availability of higher complexity devices
- No opportunity for loose conductive particles (reliability impact)
- More available sources.

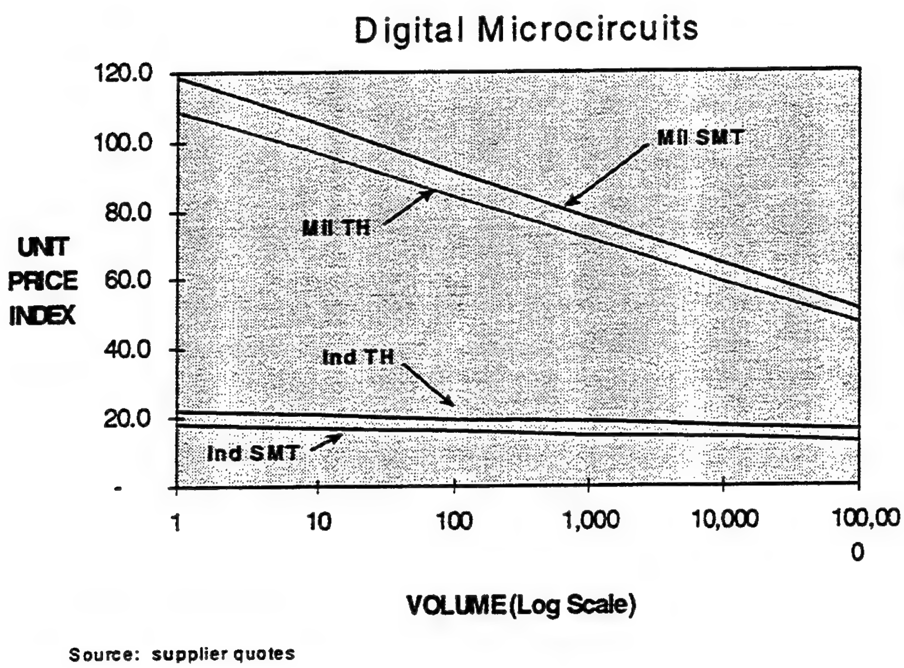
TI's Systems Group performed a pricing analysis on semiconductor devices (i.e., transistors, linear microcircuits, and digital microcircuits) to determine where the biggest cost saving might come from. The analysis performed consisted of the following five variables; each of which had several options that were considered. These variables and options are summarized in the **Table 2-2.**

The results of TI's analysis are shown in **Figures 2-1** through **2-2.** These charts are shown with the military-compliant through hole (TH) component (at the 50 piece quantity price) with a unit price index equal to 1. The comparisons to the right of the graphs provide a quick summary of component price differences when procuring 50 pieces.

The results of the pricing analysis indicate that migrating from military-compliant microcircuits to surface mount industrial microcircuits will provide the original equipment manufacturer (OEM) with significant component price savings.

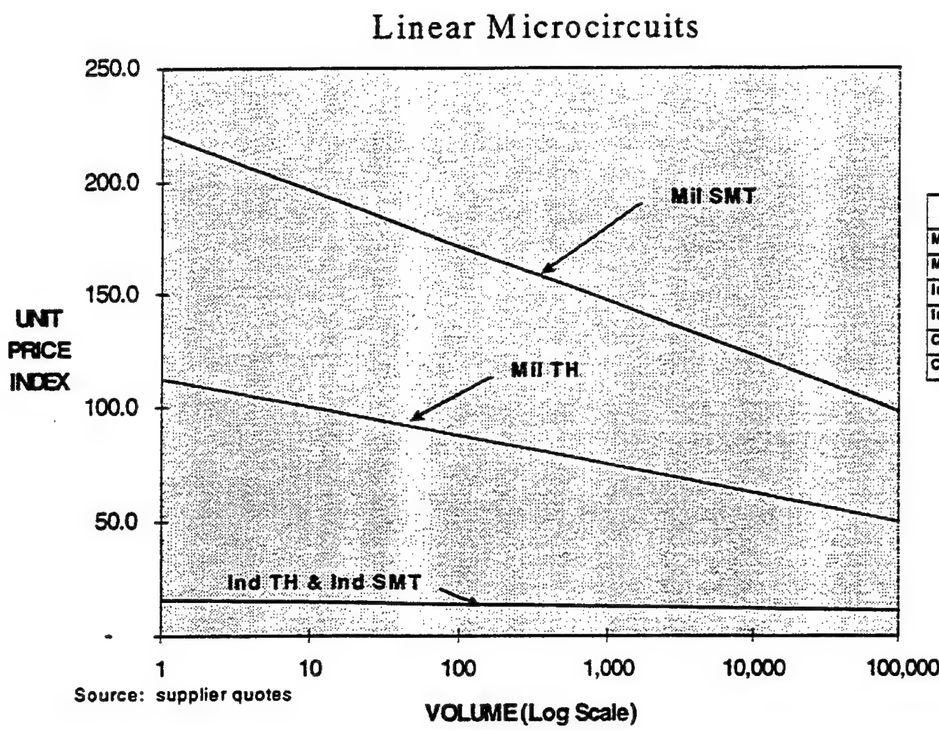
Table 2-2. Pricing Analysis Variables

Component	Supplier	Screening Level	Packaging Technology	Procurement Quantity
a	u	Military compliant	Through hole (TH)	50
b	v	Industrial temperature (non-military)	Surface mount technology (SMT)	100
c	w	Commercial temperature (non-military)		1,000
d	x			10,000
e	y			100,000
f	z			
etc.				



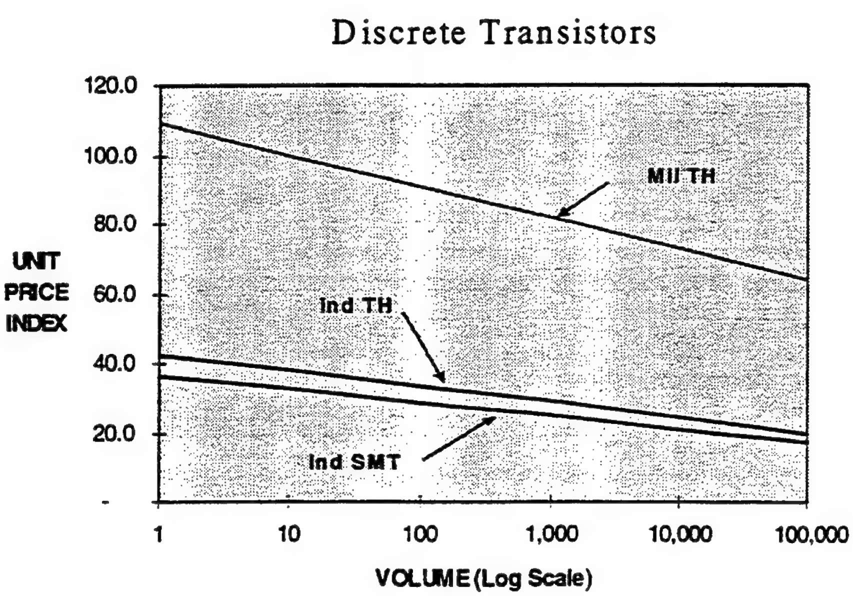
Type	Compared to Mil TH
Mil SMT	+9%
Mil TH	---
Ind SMT	-83%
Ind TH	-79%
Comm SMT	-85%
Comm TH	-82%

Figure 2-1. Pricing Analysis of Digital Microcircuits



Type	Compared to Mil TH
Mil SMT	+96%
Mil TH	---
Ind SMT	-82%
Ind TH	-82%
Comm SMT	-90%
Comm TH	-89%

Figure 2-2. Pricing Analysis of Linear Microcircuits



Type	Compared to Mil TH
Mil SMT	+305%
Mil TH	---
Ind SMT	-62%
Ind TH	-56%
Comm SMT	-18%
Comm TH	-64%

Source: supplier quotes

Figure 2-3. Pricing Analysis of Discrete Semiconductors

2.1.3 Microcircuit Technology Trends

Technology and market trends are the two that have immediate impact to fielding military electronic applications. The market trend and direct impact to the user of military-compliant microcircuits has been addressed. The availability—both current and future—of military compliant microcircuits is a major concern to all suppliers of military electronics. The continuing advances in technology will also be a major factor in availability of military-compliant microcircuits.

Microcircuit manufacturing return on investment has produced significant improvements to the quality and reliability of microcircuits. While both military and non-military microcircuits benefit from these improvements, the significantly higher volume that is produced for non-military microcircuits has reaped the largest improvements. To improve yield, quality, and reliability, the large volume of non-military microcircuits has resulted in very highly automated manufacturing processes. Device geometry and packaging are two major areas of technology advances, that may significantly impact the availability of future military-compliant microcircuits.

Device geometry. To achieve advances in technology, component manufacturers are required to continue to shrink component geometry, increase device capability, and improve component quality and reliability. Since many manufacturers do not have the capital resources to fund a $1 billion wafer fabrication facility, they are reducing their investment risk with either joint ventures or procuring capability from a third party. Return on investment is a major factor in determining which market(s) the manufacturer will support.

Component geometry scaling (listed in **Table 2-3**) will reduce the availability of currently available components as devices get smaller and technology advances, the emphasis for product support will be on the higher revenue generating products.

Device Scaling. The geometry used by components continues to shrink. Gate lengths continue to reduce in size, gate density increases, and number of devices processed per wafer increases. The impact of this trend is shown in **Table 2-3**. One of the more subtle impacts of this is the migration from the traditional power supply voltage of 5.0 volt to lower voltages.

Table 2-3. Device Geometry Matrix

Time Period	Common Gate Size (microns)	Wafer Size (inches)	Gate Density	Supply Voltage
20 years ago	10.00	3	1,000	5.0
15 years ago	5.00	4	30,000	5.0
10 years ago	2.00	6	75,000	5.0
8 years ago	1.20	6	125,000	5.0
6 years ago	0.80	8	500,000	5.0
3 years ago	0.65	8	1,000,000	5.0 or 3.3
Present	0.50	8	4,000,000	3.3
Nearing volume production	0.35	8	8,000,000	3.3
Soon to be released	0.25	8 to planned 12	Unknown	3.3 volt or less
Volume production within 3 years	0.18	12	Unknown	Unknown

Device Packaging. The industry has made a rapid transition to SMT components. The advantages of this style package include reduced size (increased packing density) and increased automation.

The microcircuit industry is dominated by plastic packaging where the military users have traditionally used lower volume higher cost hermetic packages. Today's plastic SMT packages are predominately leaded. Component leads allow for mismatches in temperature coefficients of expansion between the component and the printed circuit board (PCB). Leaded components provide improved solder joints and vibration/shock capabilities over devices that do not have leads (e.g., military ceramic SMT lead-less chip carriers). The use of leaded components can also promote the use of less expensive PCBs.

Future package trends include higher packing density with multi-chip modules (MCM), chip scale packaging, and ball grid array (BGA). With the exception of MCM, these packaging trends are being driven by high volume non-military applications. Availability of technology will be driven by package styles supported by microcircuit manufacturers.

2.1.4 Perceived Concerns and Risk Mitigation of Using PEMs

The major concerns of military-compliant microcircuits users are related to the comfort factor that comes from a known process. The following concerns have been identified for risk mitigation associating with PEM utilization (this procedure could also be used when selecting military-compliant microcircuits).

- Electrical performance
  - Specifications or documentation and change notification
  - Current and long-term part stability
- Physical performance
  - Plastic packages
  - Military screens
  - Assembly issues
- Reliability
  - Military screens
  - Infant mortality rate
  - Initial product release tests
  - Long term reliability
- Documentation (data sheets)
- Availability
  - Short term (allocation, lead times)
  - Long term (obsolescence, life cycle).

2.1.5 Product Obsolescence

There have been several recent changes in the military-compliant IC market; for example, during 1995 and 1996, the following key suppliers exited the military-compliant microcircuit market:

- Altera
- AMD
- Intel

- LSI Logic
- Motorola
- Philips
- VLSI Logic.

Two years ago, there were four suppliers supporting the military market that were listed among the top 10 in worldwide semiconductor sales. Today, only 1 of these suppliers continues to support the military market. There may be various reasons for the exit from the military market, but most of these decisions appear to have been financially based. The military market impact, as well as an increase in technology turnover rates (which impact all microcircuits, not just the military market) is seen by the large number of components that are becoming obsolete. Replacement components for these devices are often not available on a military-compliant basis.

2.1.6 Know Your Suppliers

The following questions should be asked of a non-military PEM supplier:

- May I have a copy of your reliability and quality test(s) report?
- What improvements have been made since the data has been collected?
- How many different plastic molding compounds are used?
- How many different assembly sites are used?
- How do I identify the material(s) and assembly site(s) used when reviewing your reliability and quality test reports?
- Where is the majority of product being back-end assembled?
- For specific devices, may I have a copy of your product release data package?
- For specific devices, which materials and which assembly site(s) are used?
- What qualification tests are performed when a process is first released.
- What qualifications are performed when a process is modified?
- What tests and what frequency are reliability monitors performed?
- May I have a copy of your supplier's data sheet for the mold compounds that you use?
- What is the device lead finish?

2.1.7 Component Performance Monitors

When using non-military microcircuits, the manufacturers will often use the following process reliability monitoring tests. This data supplements their statistical process controls (SPC) and could be used to assist an OEM in assessing the suitability of products to work in a given design.

Table 2-4 lists examples of data monitored during the destructive testing.

Table 2-5 provides a matrix of manufacturer reliability monitoring programs. The assessment of supplier testing should not be performed on a single occurrence. It is recommended to periodically re-assess the test results.

Table 2-4. Basic Reliability Monitoring Data

Operating life test	Test used to ensure that the supplier's die fabrication process is reliable. Specific interest from this test is to assess the suppliers adequacy of burn-in and identify any potential wear out conditions.
Temperature cycling and thermal shock	Test used to determine the reliability of the manufacturer's design and assembly processing techniques. Of specific interest are the failure mechanisms resulting from the temperature coefficients of expansion for different materials.
HAST or 85/85 (plastic only)	Combined temperature and humidity test used to determine the adequacy of the supplier's selection of materials and manufacturing processes. Of specific interest are the failure levels and mechanisms resulting from contamination (material and external) levels and the adequacy of die coatings.
Autoclave (plastic only)	Test used to determine the adequacy of the supplier's selection of materials and manufacturing processes. Similar to HAST or 85/85, but is performed with devices unbiased-biased and under pressure.

2.1.8 Common Inputs from Microcircuit Suppliers

The following list contains comments and concerns from microcircuit suppliers on the use of non-mil microcircuits in military applications:

- Some suppliers showed concern with using commercial plastic parts in military products. Legal statements and limitation are typically addressed in most suppliers databooks
- The majority of suppliers made statements based on internal policies to ensure that they do not compete against themselves
- All suppliers want to avoid special flows. Acceptance of source control drawings (SCDs) is extremely rare in the non-military world
- Most suppliers will share the information requested, once you identify the proper point of contact
- Top-tier suppliers have data to support reliability requirements. Most of the broad-line suppliers require specific device types instead of generalizations to identify data on product lines. Without narrowing the focus for broad-line suppliers, the data would be overwhelming.
- To maintain efficient control over requested information, it is necessary to limit the number of suppliers and component variations (standardization)
- No suppliers have the exact same programs for design, qualification, and reliability monitoring. Most internal programs of top-tier suppliers are adequate to achieve high reliability.
- Because each supplier uses their own internal standards, it is difficult to compare results between suppliers. It is best to get an overall corporate perspective first, before asking for data on a specific group of devices.
- None of the suppliers recommended the use of product beyond its specified limits. Should an OEM decide to use a component beyond the supplier guarantees or tested limits, often the sample size used by the OEM for component characterizations may not be significantly valid.
- Minor process changes or processing shifts might present problems for an OEM using a component beyond what is guaranteed and tested.
- QML plastic is typically the same product as the commercial device with temperature testing and appropriate specification limit changes to meet the extended temperature range.
- System design and assembly processing of plastic microcircuits creates a different mix of technical issues than experienced with ceramic (e.g., PWB design, warehousing, assembly flow, etc.).

Table 2-5. Component Performance Monitors

Supplier	High Temp Operating Life Test—Dynamic Life Test (HTOL/DHTL)	High Temp Steady State Life Test—Static Life Test (HTSSL)	Pressure Cooker (Autoclave) Test (PCT/PPOT)	Temp Cycle	Temp Humidity Bias (THB)	Highly Accelerated Stress Test (HAST)	Low Temp Operating Life (Dynamic) (LTOL)	Thermal Shock (TSHK)	High Temp Storage Life (HTSL)
S-1	Mil-Std-883, group C, +125°C, 1000 H		168 H, +121°C, 15 psig	-65 C to +150°C, 1000 cycles	1000 H, 85% RH, 85°C	85% RH, +131°C, 100 H			
S-2		1000 H at +125°C	168 H, +121°C, 15 psig	Mil-Std-883, M1010, cond B, 1000 cycles, -55/+125°C	1000 H, 85% RH, +85°C	85% RH, +130°C, 5 V		Mil-Std-883, M1010, cond B, 1000 cycles, -55/ +125°C	
S-3	+125°C	+125°C	15 psig	-65/+150°C	85% RH, +85°C				
S-4	168H at 150°C	168 H at 150°C to 1000H	15 psig, 121°C, 168 H, 100% RH	Mil-Std-883, M1010, cond C, -65/+150°C and JEDEC22-A104, cond B, -40/+125°C, 100 to 1000 cycles		29.9 psig, +140°C, 85% RH, 128 H	-45°C, 1000 H		
S-5	Mil-Std-883, M1005, cond D, 1000 H, +125°C		JEDEC22-A102, 30 psia, 100% RH, +121°C	JEDEC22-A104, -65/+150°C	JEDEC22-A101, 85% RH, +85°C	JEDEC22-A110, 85% RH, +130°C		JEDEC22-A106, -65/+150°C	
S-6	+125°C, 1000 H		+121°C, 15 psig, 160 H	-65/+150°C, 1000 cycles	1000 H, 85% RH, +85°C				
S-7	+125°C, 1008 H	+150°C, 1008 H	+121°C, 15 psi, 100% RH, 96 H	-40°C for 15 minutes, +85°C for 15 minutes, +1000°C	1008 H, +85°C, 85% RH, 4 V		-25°C, 1008 H, 4.5 V	-55°C for 5 minutes, +125°C for 5 minutes, 700°C	
S-8	+150°C junc, 1000 H	+150°C junc, 1000 H	168 H, 15 psig, +121°C	-65°C to +150°C, 500 cycles	1000 H, 85% RH, +85°C	85% RH, +130°C, 100 H	-10°C junc, 1000 H		150°C, 1000 H
S-9	1000 H at +125°C	1000 H at +125°C or 240 H at +155°C	240 H, 15 psig, +121°C	Mil-Std-883, M1010, cond C, 1000 cycles, -65/+150°C	1000 H, 85% RH, +85°C	JEDEC22-A110, 85% RH, 50 H			
S-10		JEDED-Std-26A-A102	Mil-Std-883, M1010, cond C, -65/+150°C and JEDED22-Std-A104, cond B, -40/+125°C, 100 to 1000 cycles	JEDED-Std-26A-A101, 85% RH, +85°C, unbiased				JEDED22-Std-A106, cond C1, -65/+150°C	
S-11	256 H at 145°C	2,000 H at 145°C	96 H, +121°C, 2 atmospheres	Mil-Std-883, M1010, cond C, 500 cycles, -65/+150°C	1,000 H, 85% RH, 85°C, 5V			Mil-Std-883, M1011, cond C, 100 cycles, -65/+150°C (optional)	

2.2 EXTENDED TEMPERATURE EVALUATIONS ON 686 PEMS

A total of 686 commercial temperature-grade (0 to 70°C) PEMs were electrically tested by DS&E's Component Test Facility (CTF) at the extended military temperatures (-55, +25, and +125°C). Selections of these PEMs were primarily based on the CTF's electrical test program availability. These test programs were previously generated by CTF in accordance with the military's Joint Army/Navy (JAN) specification as part of DS&E's incoming test flow for the standard ICs. The JAN specification signifies the standardization of the electrical parametric testing for the compliant suppliers and their ICs, and not all Mil-ICs (i.e., Mil-Std-883 compliant) are JAN qualified. Although the CTF's JAN test programs are unable to address the IC supplier's specified value and conditions accurately, they can be used effectively for assessing the JAN baseline capabilities at the extended military temperatures.

The extended Mil-temp test results for the 686 PEMs and listed in **Table 2-6**. The 686 tested PEMs were obtained from four different suppliers (A to D) with date codes from 1994 to 1996. With the exception of 482 digital PEMs purchased from distribution, all remaining 174 linear PEMs were obtained as samples from the selected commercial suppliers. Names of the suppliers and specific ICs will not be disclosed in this study, since they add no value for an objective baseline comparison. The commercial (com) and industrial (ind) temp-grades are defined as 0 to 70°C and -40 to +85°C respectively. Each failure is an independent failure such that failures at cold and hot are not the same device. All ICs tested are in plastic dual-in-line packages (PDIP) with pin counts from 14 to 20 pins.

Table 2-6. Results of 686 Commercial PEMs Tested Against the Mil-Temp Electrical Specifications

Supplier #	Digital (D)			Linear (L)			Total			Failures		Failures (%)
	#P/N	Com	Ind	#P/N	Com	Ind	#P/N	Com	Ind	-55°C	+125°C	per Supplier
A	18	482		3	69		21	551		2 (L)	8 (L)	1.8
B				3	75		3	75		1 (L)		1.3
C				2	15	15	2	15	15			0
D				2	15	15	2	15	15			0
Sub-Total				10	174	30	28	656	30	3 (L)	8 (L)	
Total	18	482		10	204		28	686		11 (L)		1.6
% Failures		0			5.4			1.6				

2.2.1 Final Test Results

The data shown in **Table 2-6** has been updated from the AMSUCP Interim Report to reflect the final test results of 10 total supplier-A PEM failures (extended Mil-temp rejects) in place of the initially reported 12 rejects. These initial 12 rejects were subsequently returned to the supplier A to confirm the respective failure mode of the PEMs. Supplier A confirms all 8 initial high-temp rejects pass their commercial specifications but failures did occur at the extended +125°C for the off-state output current (I_{OZ}) parameter. Two of the initial 4 Mil's cold-temperature rejects were tested good at -55°C for the high-level output voltage (V_{OH}) paramter. The remaining 2 Mil's cold-temperature failures for the differential input voltage sensitivity (V_{TH}) parameter were

unable to be confirmed because of the possible electrical over stress/electrostatic discharge (EOS/ESD) damage exhibited on the devices (the VCC pin on both units are shorted to ground).

The test results of these 686 PEMs demonstrated that commercial-temperature grade PEMs performed extremely well in the extended military temperature environment in reference to their over 98-percent test yield. No noticeable performance differences were observed between the commercial and industrial temperature-grade PEMs based on a limited 60 samples (from two suppliers) tested. Test data also suggested that digital PEMs are more temperature robust than their linear counterparts. As shown in the **Table 2-6**, digital PEMs possessed 100-percent test yield for 482 parts tested versus approximately 95-percent pass yield for the 204 linear PEMs tested. Assessing the commercial extended Mil-temperature failure distribution of these PEMs, it is concluded that a single supplier and single part-type contributed approximately 91 percent of failures or 10 of 11 Mil-temperature rejects. The relative failure rate on this part-type is 40 percent, based on the 25 devices tested. The test data also suggested that there is opportunity to improve the extended-temperature test yield by the elimination of the marginal devices via an effective supplier and part selection process. An effective part and supplier selection process will be addressed in Subsection 5.3 and Section 6 PEM Implementation Framework.

2.3 EXTENDED TEMPERATURE EVALUATIONS ON 78 ASSEMBLED AND FIELDED PEMS

This is an ongoing study via a collective research effort with the University of Maryland's CALCE Research Center, Army Research Labs, Delco Electronics, Honeywell, and Navy-Crane for the analysis of possible PEM degradation in stored Sonobuoy assemblies. This joint research effort was intended to leverage the expertise of each member, and to retrieve and evaluate the aged PEMs from the Navy's Sonobuoy assemblies cost-effectively. Navy Sonobuoys have been used extensively since the early 1950s to detect the movement of submarines. One producer, Magnavox Electronic Systems Company, has shipped over 4.7 million units.[5] They are deployed from airplanes or helicopters and separate on impact into a hydrophone assembly for sound detection and a surface transmitter for sending detected signals to the fleet. The operational life of the system, which can be as short as 9 hours, is determined by the programmed requirement and the battery life.

2.3.1 Test Results

DS&E has recently completed an extended Mil-temperature evaluation of 78 Sonobuoy PEMs and found them well within the Mil-temperature limits of the databook. These PEMs are the standard commercial-temperature grade (0 to 70°C) ICs with the 8-lead PDIP. They were removed (desoldered) from the Sonobuoy assemblies at Crane and subsequently transported to DS&E at Lewisville, Texas for electrical testing. Knowing that the overall Sonobuoy project will be continued for further reliability evaluations (i.e., PEMs moisture reliability), the focus here is primarily on the extended temperature assessment of the 78 assembled and field-stored Sonobuoy PEMs. The test results and relevant data of these PEMs are shown in **Table 2-7**.

The exact traceability of the location and duration of storage of these Sonobuoy assemblies is uncertain at this time. Available data for the Sonobuoys from which these 78 PEMs were collected suggests that they were manufactured in 1984 or thereafter, as evident by their date codes. These Sonobuoys have also been aged as a result of various assembly processes, system integration/tests, transportation (possibly transported by ship/truck and shipped to Norway) and storage (from uncontrolled warehouse to possibly outside in containers). The Sonobuoy design used a non-hermetic seal to protect its assemblies and components environmentally during storage and operation.

Table 2-7. Results of 78 Sonobuoys' PEMs Tested Against the Mil-Temperature Electrical Specification After 2 to 12 Years of Handling and Storage in Various Environments from the Date of Initial System Production

Part Type	Description	Available Since	Number Tested	Number Failed	Date Code
TL062CP	Op-amp	Nov 1978	6	0	84 to 86
TL071CP	Op-amp	Sep 1978	70	0	84 to 86
TL082CP	Op-amp	Feb 1977	2	0	84 to 86

2.3.2 PEM Product Life and Availability—An Observation

Additional inquiries were made to the supplier (TI) regarding the on-going availability of these op-amps because of the perceived notion of the short product life cycle of commercial ICs. It was surprising to learn that these op-amps are still in production today; but most overwhelmingly they have been in production since the late 1970s. This demonstrated that some commercial ICs (PEMs) do possess a longer product life. Because of the ongoing demand exerted by the automotive and telecommunication markets, it is not surprising that today's commercial suppliers are enhancing IC temperature robustness to meet these market demands. According to TI's Linear Product Group, all their new and process improved op-amp products (as an example) have been characterized in the extended temperature-range of -40°C to +125°C to optimize their PEM applications (i.e., for the automotive market). In spite of this "auto" temperature-range availability, it is not listed in today's TI databook. Military OEMs could leverage this extended-temperature product flow to optimize their IC selection tradeoff. In essence, effective supplier communication is critical to the success of PEM selection and utilization. In Section 6, the overall market realities, PEM characterization, and supplier teaming will be further exploited.

2.4 CCA BENCHMARK EVALUATIONS: MILITARY VERSUS COMMERCIAL PARTS

This primary objective of this study was to assess the environmental effects of commercial temperature grade (0 to +70°C) PEMs at the assembly level via the benchmarking of three PEM CCAs and three military IC CCAs. The environmental testing consisted of temperature cycling and vibration.

2.4.1 CCA Test Setup

An existing video processor (VP) CCA was chosen for this evaluation. The VP CCA has 55 digital ICs comprised of 18 different part types, all of which are in a dual in-line package (DIP). Three CCAs were built using military-compliant ICs specified to operate over the temperature range of -55 to +125°C. Three additional CCAs were built using the commercial equivalent PEMs (all from the same supplier) with the exception of one part type (five of this part type are used on the VP CCA) that was not available in the PEM package. All six of these CCAs went through the normal military production assembly flow at the same assembly line (location) with one exception: the commercial CCAs were subjected to a pre-flow solder bake of 105°C for 4 hours. While it is generally accepted that pre-flow solder bake is not required for PEMs in a DIP package, it was decided to perform this bake to remove "popcorning" completely as a variable during subsequent CCA testing. Also, all six CCAs were conformally coated with a silicone resin compound (Dow Corning 1-2577) as part of the normal production assembly flow.

The CCAs were installed (one at a time) into their next higher assembly, the radar interface unit (RIU) line replaceable unit (LRU), as shown in **Figure 2-4** for testing. In an actual use environment, this LRU is installed into a pod with other LRUs as shown in **Figure 2-5**. This pod is mounted on the F-16 under the fuselage where it is subjected to a harsh environment. To moderate this environment, an environmental control unit (ECU) is an integral part of the pod. The ECU circulates liquid coolant through the spine of the pod. The spine serves as the heat sink (or cold plate) for all of the LRUs. For purposes of this testing, the CCAs were tested at the LRU level. The LRU was not installed into a pod.

The CCA evaluation test flow is shown in **Figure 2-6**. The test flow was designed to maximize the number of test environments under the constraints of test chamber availability.

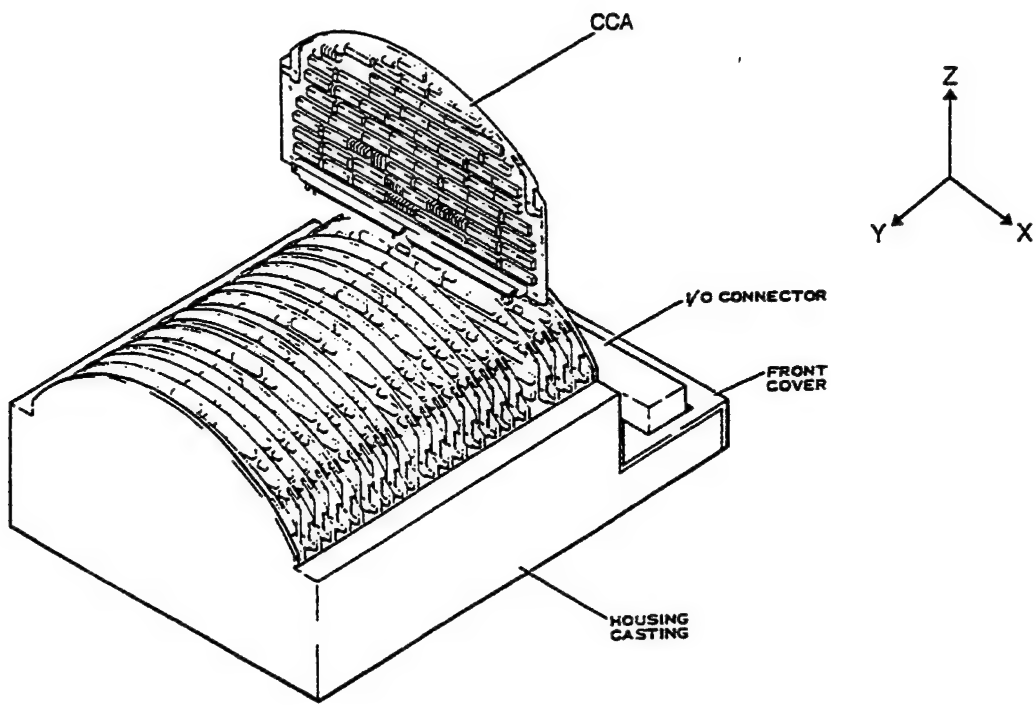


Figure 2-4. VP CCA Installation into RIU LRU

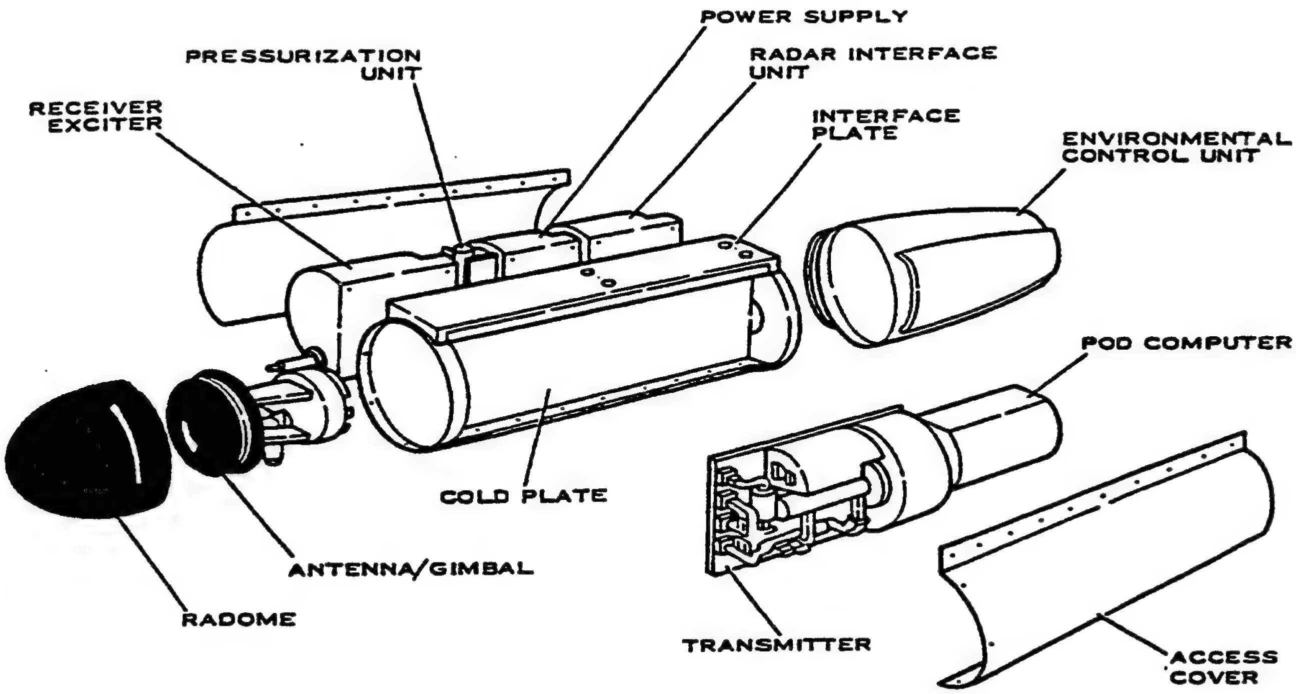
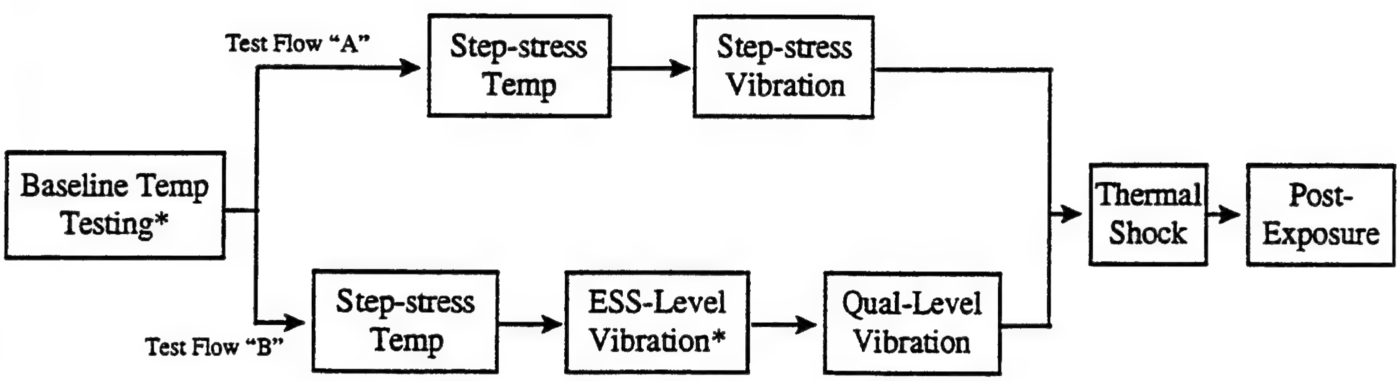


Figure 2-5. RIU LRU Installation into Pod



* Functional testing performed during environmental exposure

Figure 2-6. VP CCA Evaluation Test Flow

2.4.2 Baseline Temperature Testing

The first testing performed was to test the boards functionally over the system operating temperature range requirements. The temperature requirements for this system are from -54 to +71°C. However, due to the presence of the ECU, this LRU only experiences a temperature range of approximately -50 to +50°C. Therefore, each of the six CCAs were tested at a chamber temperature of -50, +25, and +50°C. The CCAs were installed one at a time into the LRU and the LRU was soaked at each temperature extreme until it had stabilized at that temperature. Following stabilization, a functional test was performed twice on the VP CCA. One VP functional test takes approximately 9 minutes to run. As summarized in **Table 2-8**, all six CCAs passed this testing.

Table 2-8. Baseline Temperature Testing Results

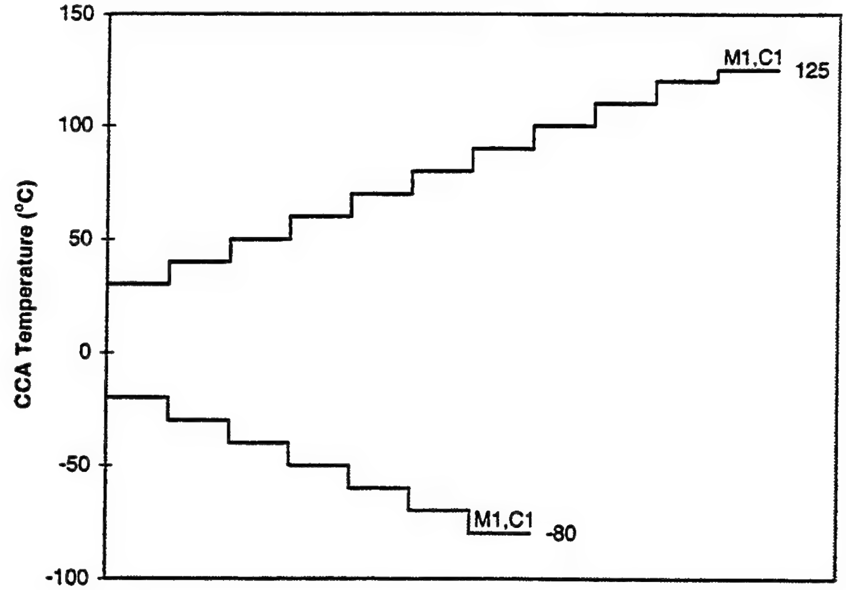
Unit Under Test	-50°C	+25°C	+50°C
Military CCA no. 1 (M1)	Passed	Passed	Passed
Military CCA no. 2 (M2)	Passed	Passed	Passed
Military CCA no. 3 (M3)	Passed	Passed	Passed
Commercial CCA no. 1 (C1)	Passed	Passed	Passed
Commercial CCA no. 2 (C2)	Passed	Passed	Passed
Commercial CCA no. 3 (C3)	Passed	Passed	Passed

2.4.3 Test Flow "A"

Following the previous baseline testing, two of the six CCAs (M1 and C1) were subjected to rapid step-stress temperature and vibration testing in a specialized test chamber. This chamber has the ability to achieve very high temperature transition rates and can perform six degrees-of-freedom (6-DOF) vibration.

One each of the military (M1) and commercial (C1) version CCAs was subjected to the temperature profile shown in **Figure 2-7**. The LRU was soaked at each temperature step until it had stabilized at that temperature (approximately 5 minutes). Following stabilization, a functional test was performed on the VP CCA. This temperature step testing was continued until the CCA under test failed. During the high temperature step test, both the military and commercial CCA failed at +125°C. Following the failure, the temperature was reduced to +120°C where both CCAs passed. During the low temperature step test, both the military and commercial CCA failed at -80°C. Following the failure, the temperature was increased to -75°C where both CCAs passed. These results indicate that both the high and low temperature failures were not catastrophic in nature, but were a recoverable functional (electrical) failure. The functional failure most likely resulted from timing problems induced by component parameters shifting at the temperature extremes.

Following the temperature testing, these two CCAs (M1 and C1) were subjected to step-stress 6-DOF vibration in accordance with the profile shown in **Figure 2-8**. The LRU was maintained at each vibration step for 10 to 15 minutes during which a functional test was performed on the VP CCA. The vibration step testing was continued until the limits of the chamber were reached at about 30 *g*RMS. Both VP CCAs passed the vibration testing; however the LRU did experience some non-relevant failures on three of the other CCAs in the LRU (these three CCAs were not VP CCAs, but are necessary for the LRU to function properly).



Mx - Military CCA failure point
Cx - Commercial CCA failure point

Figure 2-7. Step Temperature Profile for Test Flow "A"

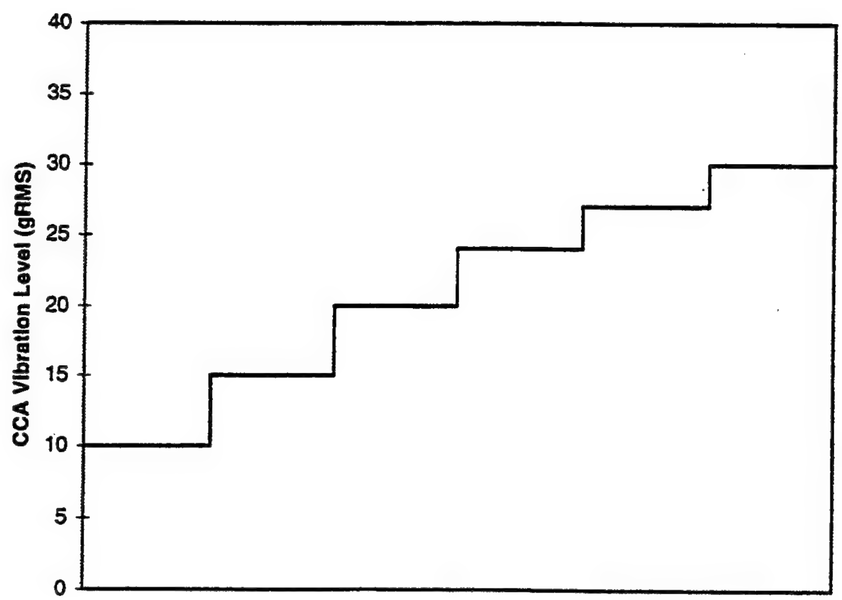


Figure 2-8. Step Vibration Profile for Test Flow "A"

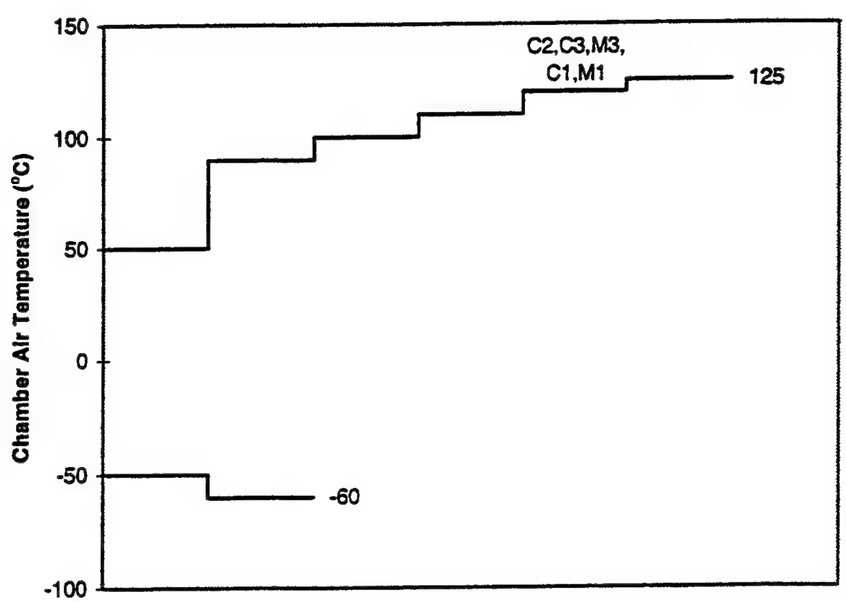
2.4.4 Test Flow "B"

The four remaining CCAs (M2, M3, C2, and C3) were subjected to a different regimen of extended temperature and vibration testing as described in the following paragraphs.

2.4.4.1 Step-Stress Temperature Testing

Temperature testing was performed as shown in **Figure 2-9**. This temperature profile differs from the test flow "A" temperature profile for two primary reasons: the chamber in which this testing took place has a maximum cold temperature limit of -60°C; and, based on the data gathered during the test flow "A" testing, it was determined to be low-risk to start the high temperature steps at +90°C. The LRU was soaked at each temperature step until it had stabilized at that temperature. Following stabilization, a functional test was performed on the VP CCA. This temperature step testing was continued until the CCA under test failed or the chamber temperature limits were reached. All CCAs passed at -60°C. During the high temperature step test, CCAs C2, C3, and M3 failed at +120°C. Following each failure, the temperature was reduced to +110°C where each of the CCAs passed. CCA M2 passed all of the high temperature tests including the one at +125°C. As was the case during the test flow "A" temperature testing, these failures were not catastrophic.

Because of the differences in the high temperature failure point between these four CCAs and the first two CCAs (M1 and C1 CCAs passed at +120°C and failed at +125°C), it was decided to expose the M1 and C1 CCAs to high temperature in this test chamber. Both M1 and C1 failed at +120°C in this chamber and passed when the temperature was reduced to +110°C. Therefore, it can be concluded that the difference between the two test chamber results was a result of variations in the chamber and/or setup and not related to the VP CCAs themselves.



Mx - Military CCA failure point
Cx - Commercial CCA failure point

Figure 2-9. Step Temperature Profile for Test Flow "B"

To further pinpoint the component temperature at which these hot failures were occurring, thermocouple data was obtained during testing for each of the CCAs. **Figure 2-10** shows the thermocouple placement and **Table 2-9** shows component temperatures for three components on the VP CCA at the point the CCA failed. Since CCA M2 did not fail at high temperature, component temperatures are shown for the +125°C test. These thermocouple locations were selected based on analysis that indicated these were the hottest parts on the board.

Table 2-9. Component Temperatures at Point of Failure

Unit Under Test (UUT)	Failure Temperature (°C)	VP U25 Temperature (°C)	VP U33 Temperature (°C)	VP U42 Temperature (°C)
M1 - test flow "A"	125	129.6	128.8	129.1
C1 - test flow "A"	125	129.3	129.2	128.1
M1 - test flow "B"	120	127.1	127.0	128.1
M2 - test flow "B"	125*	130.8	129.2	130.4
M3 - test flow "B"	120	127.1	127.1	127.1
C1 - test flow "B"	120	126.2	126.6	127.0
C2 - test flow "B"	120	126.9	127.7	127.5
C3 - test flow "B"	120	127.0	128.5	127.9

*M2 did not fail during high temperature testing, so data for the highest test temperature is shown.

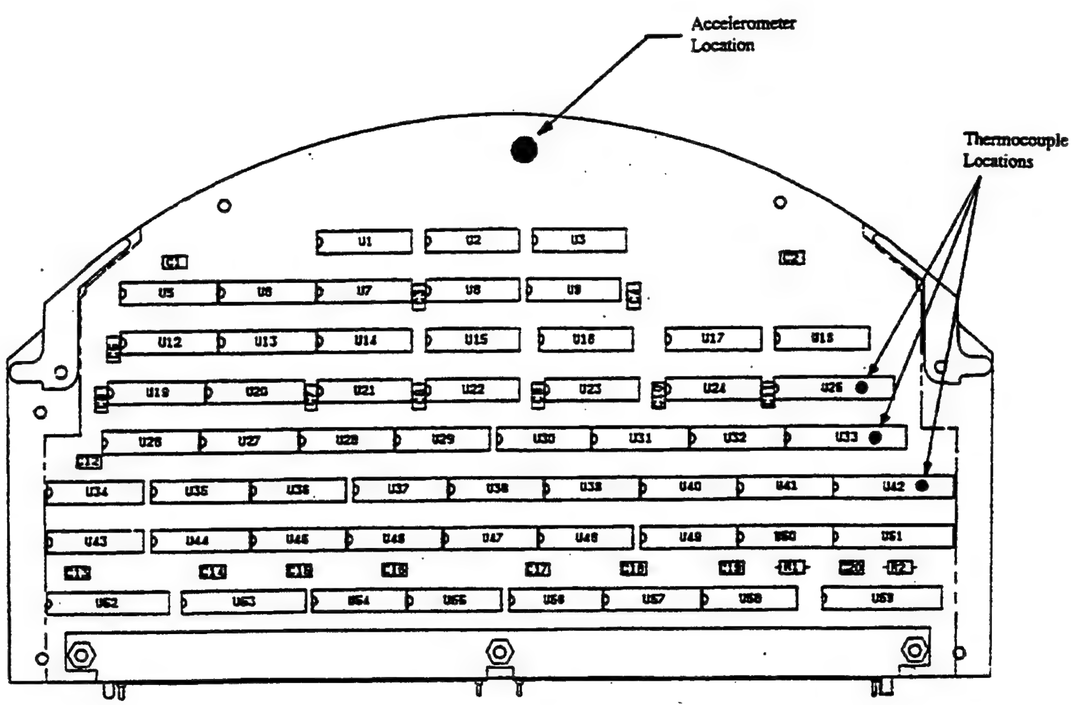


Figure 2-10. VP CCA Thermocouple and Accelerometer Placement

2.4.4.2 ESS-Level Vibration

Following the previous temperature testing, these four CCAs (M2, M3, C2, and C3) were subjected to random vibration identical to the normal production environmental stress screening (ESS) vibration. The CCAs were installed one at a time into the RIU and exposed to the 6 *g*RMS input vibration profile of **Figure 2-11.** Typical input and response profiles are shown for Y-axis vibration (axes are defined in **Figure 2-1**). **Figure 2-10** shows the accelerometer location at which this response was measured. This location was chosen because it was on the only unconstrained edge and was believed to be the point with the greatest deflection. This vibration was performed in the X and Y axes for 10 minutes per axis. A functional test was performed on the VP CCA during this vibration exposure. All four boards passed the functional tests.

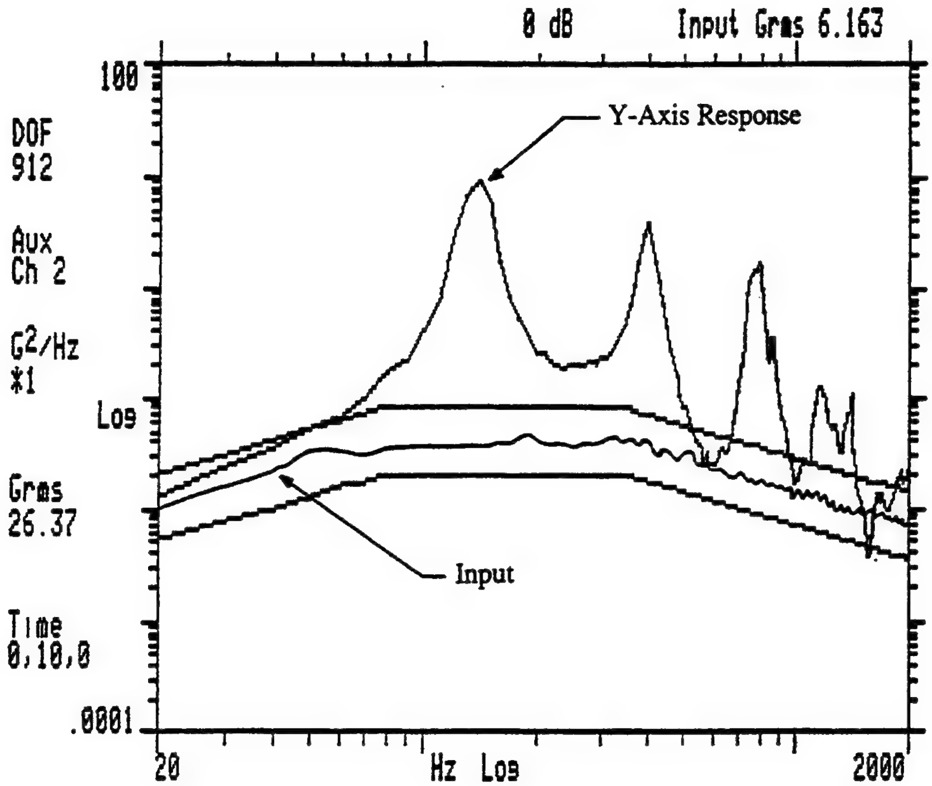


Figure 2-11. VP CCA ESS-Level Vibration

2.4.4.3 Qualification-Level Vibration

Following ESS vibration, these four CCAs were exposed to a variety of qualification-level vibration profiles as shown in **Figures 2-12, 2-13, 2-14**, and **2-15**. **Figures 2-12** and **2-13** show both the typical input and response profiles for Y-axis vibration. The vibration shown in **Figure 2-12** was performed in all three axes for 3 hours per axis at 12.6 *g*RMS. The vibration shown in **Figure 2-13** was performed in all three axes for 30 minutes per axis at 18.7 *g*RMS. **Figures 2-14** and **2-15** show only the response profile since the input and response profiles for these two tests were essentially the same. The vibration shown in **Figure 2-14** was performed in the X axis only for 5 minutes. The vibration shown in **Figure 2-15** was performed in the Z axis only for 5 minutes. The original plan was to follow, as closely as possible, the RIU qualification regiment. The main deviation was that the functional qualification vibration shown in **Figure 2-12** had to be performed non-operationally because of failures associated with the RIU test equipment. These failures were not related to the VP CCAs under test, but prevented functionally testing the CCAs during vibration exposure. Following vibration exposure, the four CCAs underwent a functional test at room ambient conditions. All four CCAs passed this testing.

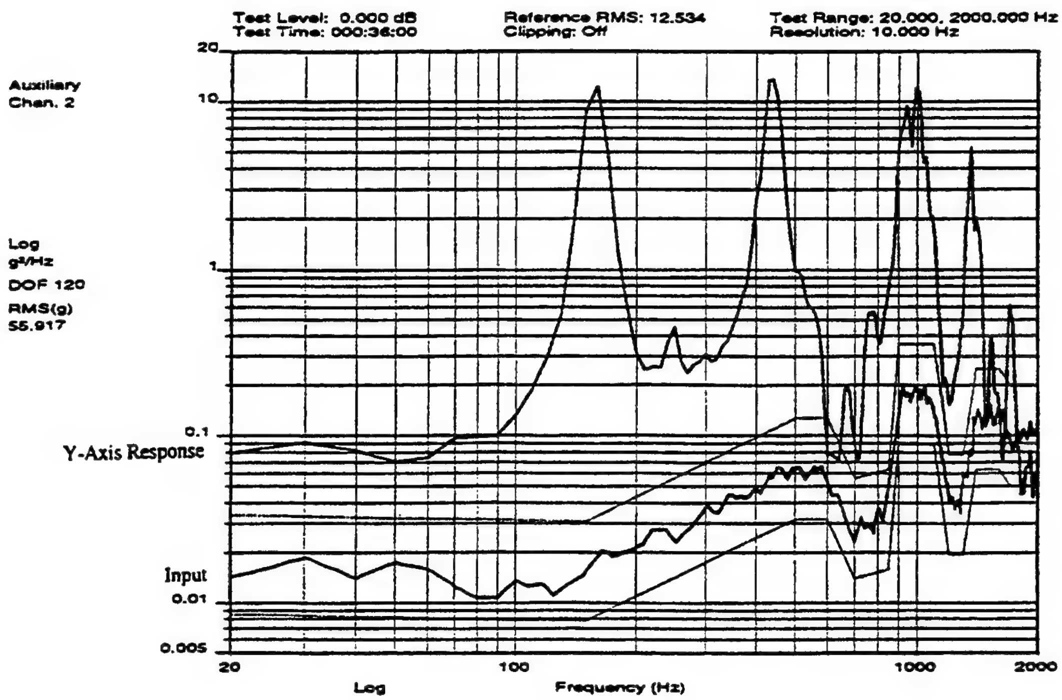


Figure 2-12. VP CCA ESS-Level Vibration

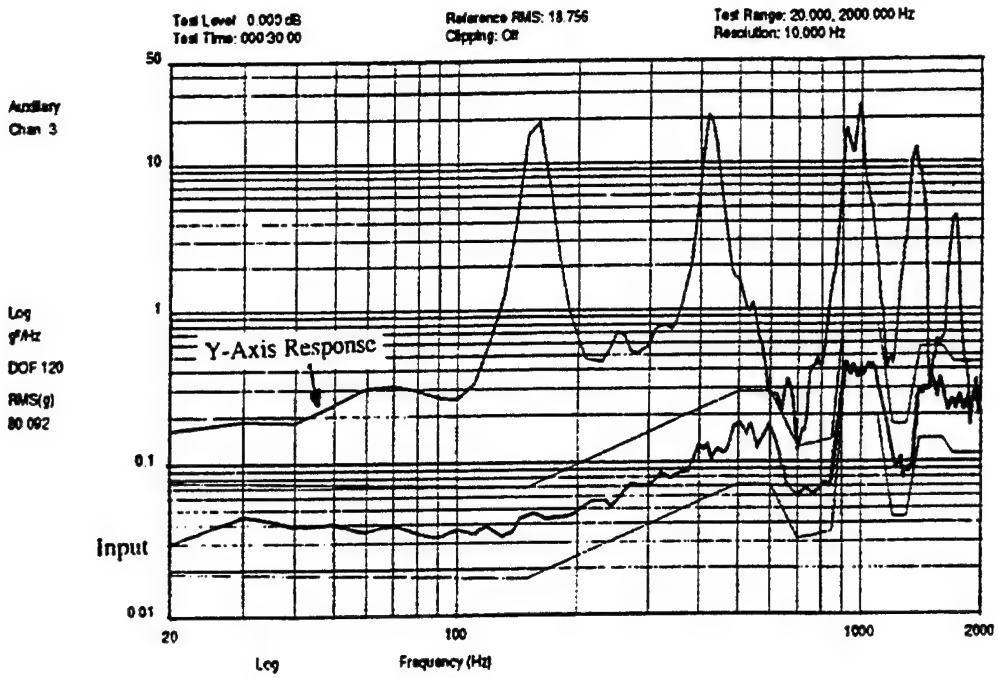


Figure 2-13. VP CCA Non-Operational Qualification Vibration

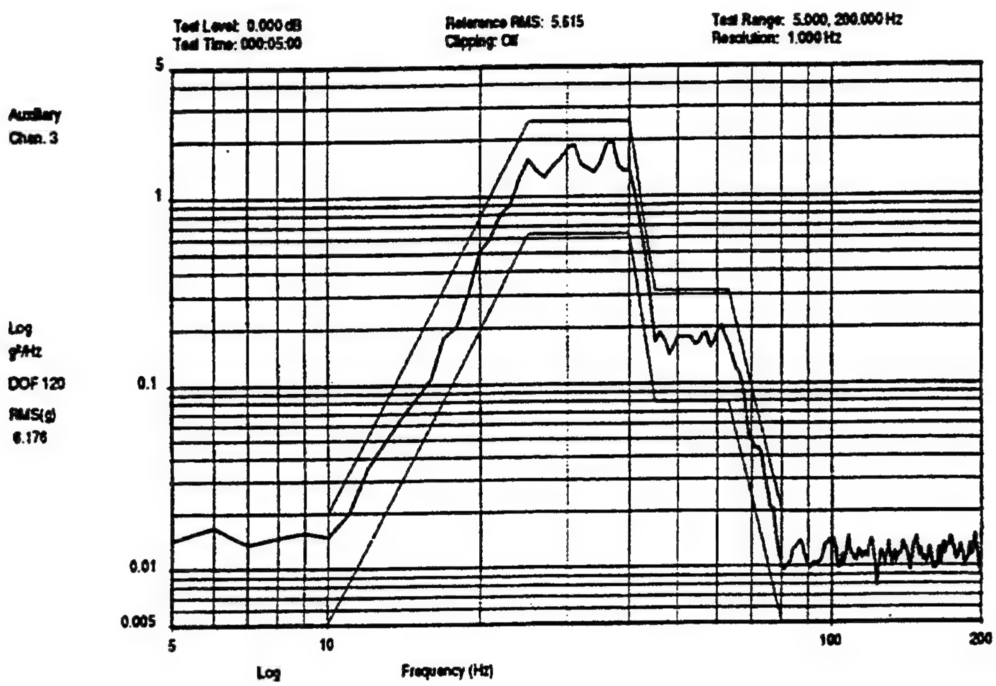


Figure 2-14. VP CCA Vertical (X-Axis) Buffet Vibration

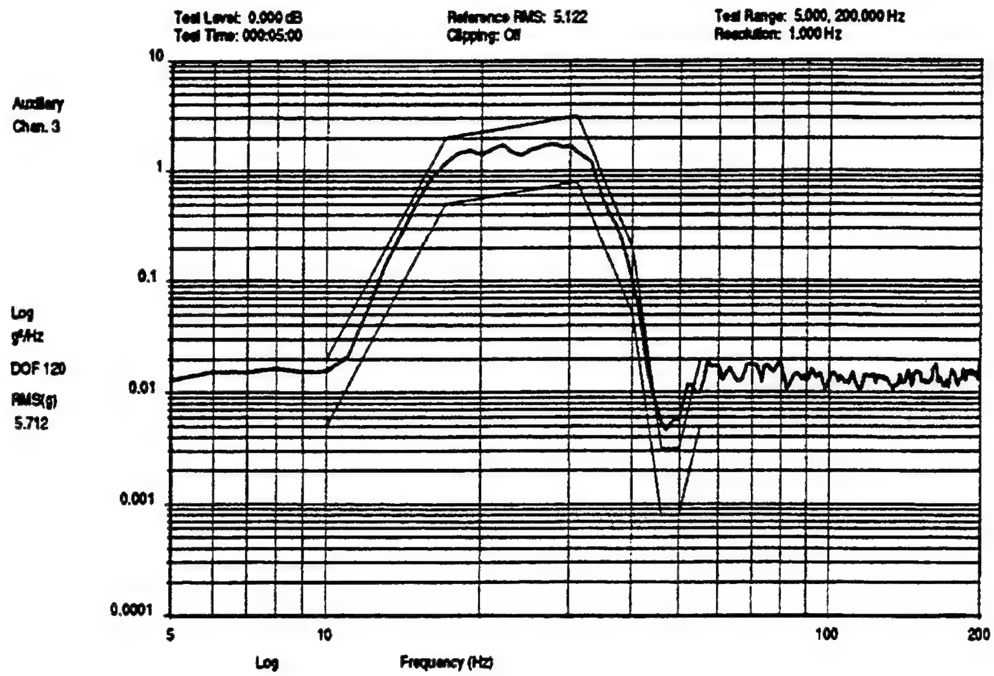


Figure 2-15. VP CCA Lateral (Z-Axis) Buffet Vibration

2.4.5 Thermal Shock

Following the test flow "A" and test flow "B" testing, all six CCAs were exposed to 30 cycles of non-operational thermal shock. The temperature extremes were -60 to +125°C with a 1-hour dwell time at each extreme. The transition rate between temperature extremes was approximately 92.5°C/second. Following thermal shock, all six CCAs were functionally tested and passed.

2.5 CONCLUSIONS

The baseline PEM assessment touches upon some basic awareness of today's BCP and utilization of PEMs. It established PEM's cost effective value for today's affordable military systems quest. This PEM awareness is also the fundamental step for the formation of the PEM implementation framework (Section 6) where the intricate realities and influences are to be exploited.

Three experimental evaluations were conducted to assess the extended temperature capabilities of PEMs. These evaluations concluded that current technology and quality-mature PEMs are profoundly Mil-temperature robust. This robustness is also influenced by the "relaxed" Mil-temperature specifications as they were derated from the standard commercial-temp's parametric limits. The test results also demonstrated that the linear ICs are less Mil-temperature robust than their digital counterpart because of their design complexity. The data indicated that the linear (analog) ICs had contributed all 11 rejects or (1.6 percent) Mil-temperature fall-out rate via the extended-temperature testing of 686 standard PEMs. However, this relatively low fall-out rate is consistent with the prior DS&E evaluation[6] on 278 commercial-temperature-grade ICs with no Mil-temperature fall-out. More significantly, 10 of the 11 rejects were caused by one part type and one supplier. Therefore, effective supplier and part selection can mitigate the marginal IC risks.

The extended temperature testing of the Sonobuoy PEMs provided an inclination that the 10- to 12-year-old PEMs remain Mil-temperature robust after they were removed from the Navy's fielded Sonobuoy assemblies. An assessment of the availability of these "aged" PEMs suggested that their design inception occurred in the late 1970s, and yet they are still in production today. It is also suggested that some of the PEMs' extended-temperature flow (product grade: -40 to +125°C) does exist although they have not been advertised through the data book (refer to Subsection 6.3.3 for further discussion). The CCA benchmarking results are also consistent with the prior DS&E study.[6] The CCA evaluations concluded that today's PEMs manufactured by the BCP suppliers can operate reliably at temperatures exceeding their specifications even after the additional stresses of assembly and environmental testing.

SECTION 3
WORST-CASE TEMPERATURE STUDY ON WORLDWIDE USAF BASES

It is cost prohibitive—and sometimes technologically impossible—to design military equipment to operate under the most extreme environmental conditions. The likelihood that a system would ever encounter such extreme conditions during its lifetime is slight. For this reason, military planners take a calculated risk and accept equipment designed to operate under environmental stresses for all but a certain small percent of the time. This section will address the likelihood that a system will experience those temperatures that are beyond its design limits.

3.1 AIR FORCE BASE SELECTION AND PROFILES

The majority of a system's operational life is spent on the ground at a military facility. With that in mind, a survey was conducted on Air Force versus. Navy bases to determine which experienced the most severe temperature extremes. Most Naval facilities are located in a coastal/marine environment that does not reach the extreme cold conditions of inland sites. Therefore, the Air Force bases were chosen as the facilities to scrutinize. The office of the Air Force Combat Climatology Center (AFCCC), which provided data for a previous study on cold temperature extremes, were tasked to provide hot temperature data.

A look at the USAF bases began with a broad screening of the all-time record lows and highs for each base. This provided an initial cut to narrow the field for analysis. The bases chosen for in-depth study were checked for the suitability of system deployment. Those bases that have been closed, are slated for closing, or don't have a runway were eliminated. The hourly weather data for the remaining bases was statistically reduced to give the probability of occurrence of such extreme temperatures.

In the past, military systems were designed to operate throughout the range of possible temperatures, regardless of how often those temperatures might actually occur. Mil-Std-210C established a method of determining the expected "Frequency of Occurrence" of temperatures that approach the extreme outer limits. From hourly data, it is possible to determine the total number of hours per month that a specific value of temperature is met or exceeded. This is usually done for the hottest or coldest months of a particular location. For example, if a temperature occurs, or is exceeded for an average of 7 hours in a 31-day month (744 hours), it has occurred roughly 1 percent of the hours in that month. The value that is equaled or exceeded 1 percent of the time is referred to as the 1-percent value. As listed in **Table 3-1,** the values of the 1-percent low temperature are the values that occur for 1 percent of the time in the coldest month of the year. Conversely, the values of 1-percent high temperature in **Table 3-2** are the values that occur for 1 percent of the time in the hottest month of the year.

Mil-Std parts are tested to -55°C at the cold temperature; a procedure that increases the cost of each part. As shown in **Table 3-1,** that temperature (-55°C) is lower than the all-time record low at the coldest USAF base. Industrial grade parts rated to -40°C would be the more cost-effective choice. Only one base would be expected to experience temperatures lower than -40°C and that would only be for 10 percent of the most severe month. The amount of restricted usage time would be minimal in comparison to the cost savings inherent in using industrial grade parts over Mil-Std parts.

Table 3-1. Statistical Representation of the Coldest Air Force Bases

Air Force Base	Years of Record	Record Low Temperature (°C)	1% Low Temperature (°C)	10% Low Temperature (°C)
Eielson, Alaska	51	-53.3	-47.1	-40.4
Elmendorf, Alaska	51	-41.7	-28.6	-21.3
Grand Forks, North Dakota	36	-37.8	-30.4	-22.1
Minot, North Dakota	47	-42.2	-29.8	-19.2
Malmstrom, Montana	53	-42.2	-28.2	-18.3

Table 3-2. Statistical Representation of the Hottest Air Force Bases

Air Force Base	Years of Record	Record High Temperature (°C)	1% High Temperature (°C)	10% High Temperature (°C)
Davis-Monthan, Arizona	54	46.7	41.1	37.7
Luke, Arizona	54	50.6	44.4	41.1
Nellis, Nevada	53	48.3	44.0	40.7
Edwards, California	54	45.6	41.1	37.4
Incirlik, Turkey	40	45.6	38.5	34.1
Dhahran, Saudi Arabia	49	48.9	45.0	41.8
Riyadh, Saudi Arabia	37	46.7	45.0	43.0

A discussion of expected high temperatures presents a different problem. Electronic parts generate their own heat while operating, so an evaluation of the expected temperatures at any location must be understood to be the surface temperatures only, without the influence of solar radiation or induced power. Therefore, all electronics are assumed to be in a steady-state condition, with no power applied, and without the influence of any surrounding electronics that may be operational. Industrial grade parts are rated up to 85°C.

The hottest part of the world where recent combat has occurred is in the Middle East. Troops stationed in Saudi Arabia, experience desert conditions. The 1-percent high temperature for this location is 45°C and the 10-percent high temperature is 43°C. These would be considered to be the hot soak conditions for the electronics. Any conclusions drawn from these statistics would have to include the expected temperature increases of the equipment when power is supplied, the length of time the system is powered on, and the influence of any surrounding heat sources (including aerodynamic heating and solar radiation).

3.2 TEMPERATURE CONDITIONS AT ALTITUDE

A decision was made to use actual data for this analysis rather than the atmospheric charts from Mil-Std-210C. Those charts constitute an unrealistic profile since they do not represent an actual occurrence, but rather a compilation of record temperatures at each individual altitude. The profiles are not vertically consistent and would never occur in nature. To find an actual worst-case atmospheric profile, a search was done to find a profile where the temperatures at altitude were the most extreme for a pre-determined ground temperature.

It is well known that temperatures decrease at high altitudes. However, on extremely cold days, there is a thin blanket of cold air that remains close to the ground. Once above this blanket, temperatures are actually warmer than ground measurements. This phenomenon causes air temperatures to be warmer than ground temperatures up to 15,000 feet. It is for this reason that temperatures at altitude on cold days are not as cold as expected. On extremely hot days, the atmosphere behaves as expected in that there is a fairly linear decrease in temperature as height increases. Aircraft flying at altitudes less than 10,000 feet will experience the most severe aerothermodynamic heating on these extremely hot days.

Figure 3-1 shows the worst-case atmosphere when ground temperature equals -40°C (the 10-percent low temperature) at Eielson AFB, the coldest permanent military facility that supports fighter aircraft. **Figure 3-1** also shows the worst-case atmosphere when ground temperature equals 45°C (the 1-percent high temperature) at Dhahran, Saudi Arabia. Dhahran was the temporary USAF base location of the most recent desert warfare. A ground temperature of 45°C equals the 10-percent high temperature worldwide.

3.3 RECOVERY TEMPERATURE ASSESSMENT

In any discussion on atmospheric temperatures at altitude for aircraft, consideration of the resultant recovery temperature must be made. Recovery temperature is a function of the ambient temperature and speed of the aircraft. For straight and level flight, the recovery temperature can be considered to be equal to the skin temperature after approximately 5 minutes of flight. Though temperatures at altitude may seem extreme, it must be remembered that an aircraft must be flying at a minimum speed to remain airborne. For cold temperatures, this is fortunate as skin friction will warm the aircraft. However, at lower altitudes on hot days, this can cause additional heating problems.

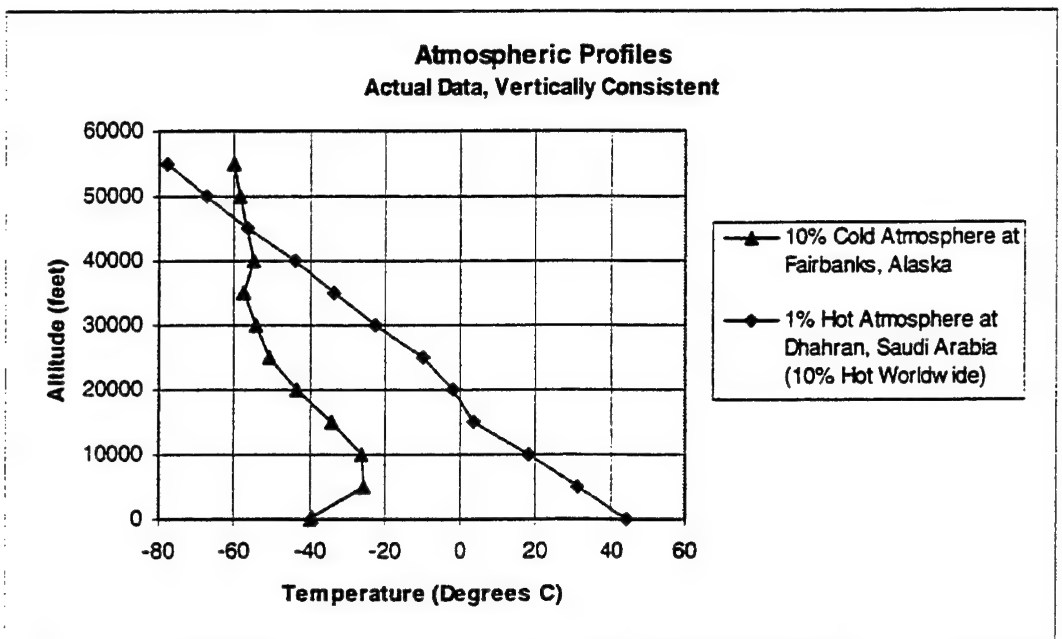


Figure 3-1. Temperature Conditions at Altitude

The heat transfer that occurs in flight because of skin friction is dependent on the following factors:

- Aircraft capability and flight characteristics at altitude
- Load-out of the aircraft (armament and fuel load)
- Length of cold/hot soak of the aircraft on the ground.

Recovery temperatures can easily be calculated for a simple, flat plate at zero angle of attack. While this is a rough representation of the mid- to aft-fuselage, the nose of the aircraft will experience hotter recovery temperatures. A more detailed calculation of the recovery temperature is unnecessary and beyond the scope of this project.

An examination of the typical mission profile for the F-16 shows the majority of flight takes place below 50,000 feet. In fact, flying above 50,000 feet requires the pilot to be outfitted in a pressure suit. Such missions are not usually carried out during peacetime because of the need to obtain a waiver for flight at those altitudes. Although it is recognized that combat missions may very well exceed 50,000 feet, those flights would likely be of short duration and high speed. The aircraft would not have enough time to cool to the expected recovery temperature and would probably fly at speeds fast enough to keep the aircraft skin temperatures above -40°C. For these reasons, it was determined that the analysis of recovery temperature effects on the F-16 would be conducted for altitudes below 50,000 feet.

The U.S. bases that reach the hottest temperatures do not keep atmospheric profile data. Consequently, the decision was made to examine the hottest base where F-16s have been stationed in combat, i.e., Dhahran, Saudi Arabia. As shown in **Figure 3-2**, the recovery temperature chart for a ground temperature of 45°C indicates that aircraft flying at high speeds and at low altitudes will experience considerable heating of the airframe. This aerodynamic heating will be conducted through the skin to the electronics and other essential systems.

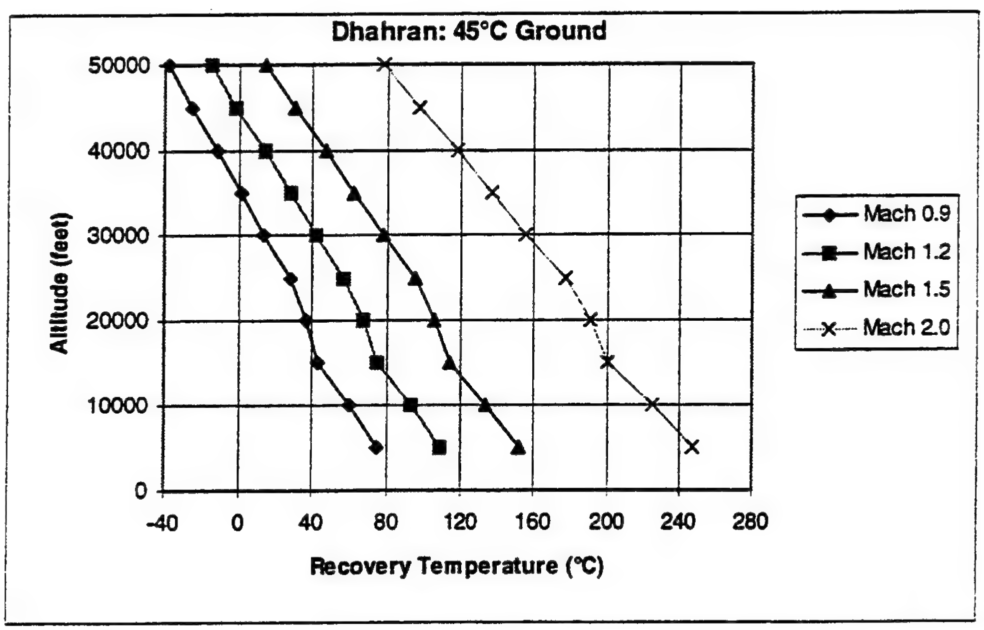


Figure 3-2. Recovery Temperature for 1-Percent High Temperature at Dhahran, Saudi Arabia (Equal to 10 Percent High Temperature Worldwide)

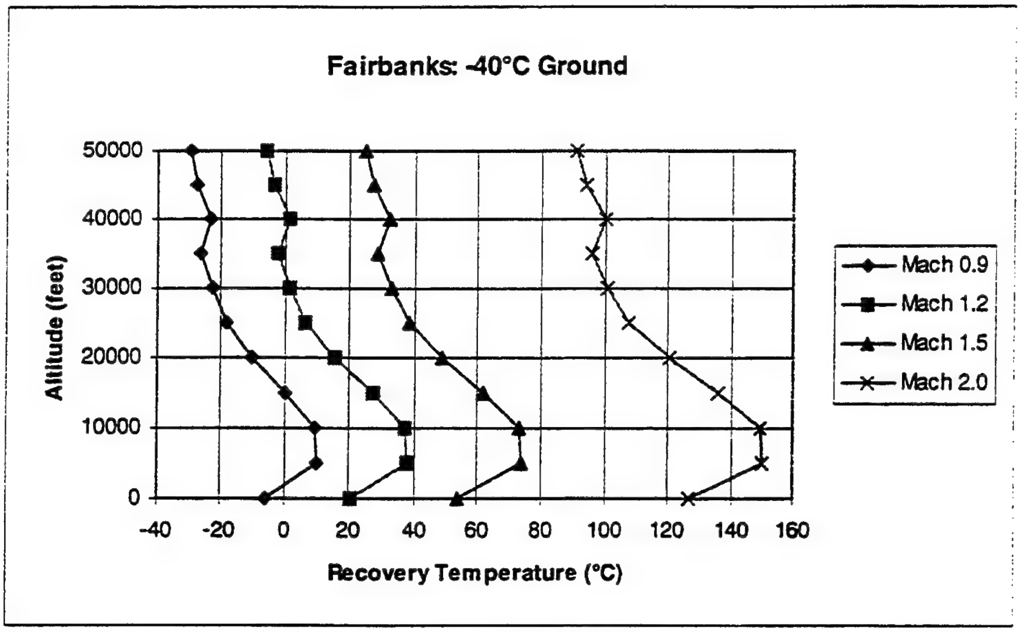


Figure 3-3. Recovery Temperature for 10-Percent Low Temperature at Eielson AFB, Alaska

The coldest temperatures where F-16s may be stationed occur at Eielson AFB in Alaska. This base uses alert shelters to warm the aircraft to their specified operating temperature before flight. Even on the coldest days, it can still be assumed that an F-16 will not be colder than -40°C before takeoff. The recovery temperature for 10-percent low temperature at Eielson AFB, Alaska is shown in **Figure 3-3.**

3.4 CONCLUSIONS

The arguments for using industrial-grade parts over military parts are many. In looking specifically at the temperature issue, a few conclusions can be drawn. Addressing the cold issue, the risk in accepting industrial grade parts is small. The probability that a part will ever experience temperatures colder than -40°C is extremely low. Of the 96 locations that were evaluated for this study, only 3 have ever exceeded -0°C. Only one of those locations would be likely to see those temperatures in any given year, and that would be for less than 10% of the month of January. It is possible that the recovery temperature could exceed -40°C at altitudes above 50,000 feet, but designing to a worst-case atmosphere for atypical missions is cost prohibitive. Aircraft are warmed to -40°C before they are powered on; this applies to the electronics as well. The cost savings in using industrial-grade parts far outweigh the slight risks involved in exceeding their cold temperature limits.

This recommendation can be made for the hot temperature issue as well. Statistics indicate that there is little risk in accepting the hot temperature limits of industrial-grade parts. It must be remembered, however, that testing of individual parts is not a true representation of the operating environment of the electronics. The parts will rise in temperature from the moment that power is applied. They will be warmed by heat transfer through the skin, and they are normally packaged very close to other electronics that are generating heat. All these factors must be considered when designing boards that will use industrial-grade parts. Thermal management techniques in board design minimize the risks encountered in the crowded boards of modern systems, whether the designer uses Mil-Std or industrial-grade parts. Allowing the designer the opportunity to use industrial-grade parts opens up the possibilities of lower system cost, more readily available inventories from which to choose, and the ability to include the latest commercial developments quickly with little risk.

SECTION 4
AVIONICS APPLICATION (F-16)

The F-16 aircraft and its avionics system configuration forms the basis for AMSUCP environmental data. The data consists of LRU requirements and IC temperature characteristics. LRU requirements include environments such as temperature, vibration, and shock gathered from F-16 LRU specifications for selected equipment in different aircraft locations. IC temperature characteristic data consists of the case temperatures for ICs located within LRUs in different aircraft locations. This data includes power-up, ground, and inflight IC case temperatures, which is based on the development history of the aircraft and equipment designs.

The following paragraphs provide descriptions of:

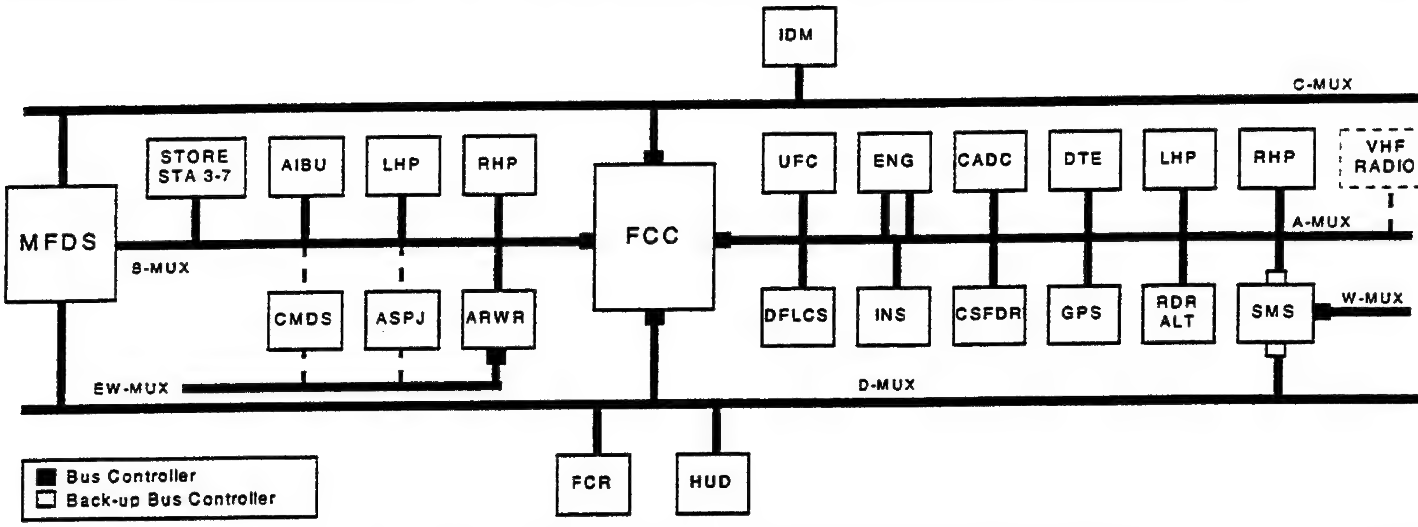
- F-16 Block 50 avionics architecture and selected LRU throughput and memory capabilities
- Levels of criticality for F-16 avionics LRUs (Subsection 4.2)
- F-16 avionics cooling system (Subsection 4.3)
- F-16 equipment locations (Subsection 4.4)
- F-16 equipment design considerations (Subsection 4.5)
- F-16 avionics environmental requirements and IC temperature characteristic data for selected aircraft locations (Subsection 4.6).

4.1 AVIONICS ARCHITECTURE

The latest F-16 avionics system configuration is the Block 50 avionics architecture, shown in **Figure 4-1**. The block designation for an avionics configuration denotes major hardware and software changes incorporated into the system to provide new functions. Also included with the designation is a letter, such as Block 50L, that denotes minor changes within a major configuration.

The Block 50 avionics system architecture is structured around distributed LRUs interconnected with six dual redundant Mil-Std-1553/1553B multiplex data buses. The F-16 avionics architecture is a distributed system architecture with centralized control. The fire control computer (FCC) is the primary bus controller for the system, controlling the A-, B-, C-, and D-muxes to schedule 1553 message traffic.

The stores management set (SMS) provides back-up bus control for the A and D muxes in the event of FCC failure and is the primary controller of the weapons multiplex bus (W-mux). The electronic warfare multiplex bus (EW-mux) is controlled by the advanced radar warning receiver (ARWR). The A-, B-, C-, D-, and EW-muxes use Mil-Std-1553/1553B protocol. The W-mux uses Mil-Std-1553/1553B protocol and a Lockheed Martin unique protocol.



AIBU	- Advanced Interference Blanker Unit	DTE	- Data Transfer Electronics	INS	- Inertial Navigation Set
ARWR	- Advanced Radar Warning Receiver	ENG	- Engine	MFDS	- Multi-function Display Set
ASPJ	- Airborne Self Protection Jammer	FCC	- Fire Control Computer	LHP	- Left Hard Point
CADC	- Central Air Data Computer	FCR	- Fire Control Radar	RDR ALT	- Radar Altimeter
CMDS	- Countermeasures Dispenser Set	GPS	- Global Positioning System	RHP	- Right Hard Point
CSFDR	- Crash Survivable Flight Data Recorder	HUD	- Head-Up Display	SMS	- Stores Management System
DFLCS	- Digital Flight Controls System	IDM	- Improved Data Modem	UFC	- Up-front Controls

Figure 4-1. F-16 Block 50 Avionics Architecture

F-16 LRUs provide the following capabilities. Targeting sensor capability is provided via:

- Fire control radar (FCR)
- HARM targeting system (HTS)
- Radar warning receiver (RWR).

Navigation capability is provided by:

- Ring laser gyro (RLG)
- Inertial navigation set (INS)
- Global positioning system (GPS)
- Radar altimeter (RALT)
- Central air data computer (CADC)
- Fire control computer (FCC).

Weapons control capability is provided via a stores management set (SMS). Data link capability is provided via the improved data modem (IDM). Cockpit displays are provided by:

- Multi-function display set (MFDS)
- Up-front controls (UFC)
- Head-up display (HUD).

Mission planning capability is provided via the data transfer equipment (DTE). Countermeasures capability is provided via electronic countermeasures (ECM) pods carried external to the aircraft and a countermeasures

dispensing set (CMDS). RF compatibility is provided via an interference blanker unit (IBU). Threat warning capability is provided by a radar warning receiver (RWR).

Commercial PEMs may be useful for LRU performance upgrades and obsolete parts replacement. F-16 avionics LRUs have very low processing and memory capabilities as compared to current computing technology, since F-16 LRUs were designed using 1970s and early 1980s technologies. **Table 4-1** lists the total, used, and percent utilization throughput and memory requirements for selected F-16 LRUs. The throughput requirements shown in the table are based on an F-16 instruction mix. When converted to a commercial standard instruction mix, these throughput numbers are approximately 7.3 times higher. As shown in the table, the FCC, SMS, MFDS, and HUD LRUs are reaching the limits of their processing and memory reserves. Also, the F-16 is starting to experience avionics parts obsolescence issues. An example of parts obsolescence is the Z8002 microprocessor that is no longer being produced by industry.

Table 4-1. Throughput and Memory for Selected F-16 Functions

	Total		Used		Utilization	
Function	**Throughput (MIPS)**	**Memory (KWords)**	**Throughput (MIPS)**	**Memory (KWords)**	**Throughput**	**Memory**
Fire control computer (FCC)	1.6	256	1.5	243	95%	95%
Stores management set (SMS)	0.34	EEPROM 128 CORE 48 SHARED 16	0.32	EEPROM 96 CORE 26 SHARED 13	93%	EEPROM 75% CORE 55% SHARED 80%
Display Processing						
Head Down (MFDS)	1.1	BBRAM 256 EEPROM 8	0.94	BBRAM 154 EEPROM 4	85%	BBRAM 60% EEPROM 50%
Head Up (HUD)	0.4	48	0.4	47	99%	97%
Misc Control (UFC)	0.12	BBRAM 16 EEPROM - PROGRAM 32 - LITERAL 32	0.06	BBRAM 11 EEPROM - PROGRAM 30 - LITERAL 22	50%	BBRAM 70% EEPROM - PROGRAM 95% - LITERAL 70%

4.2 LEVELS OF CRITICALITY FOR F-16 AVIONICS LRUS

Two levels of avionics LRU criticality were explored for the AMSUCP program. These levels are "life critical" and "mission critical." The term "life critical" is defined as an electronics system failure that can potentially cause aircraft loss and loss of life. "Mission critical" is defined as an electronics system failure that causes mission abort.

F-16 avionics LRUs are not delineated by levels of criticality because of the lack of a requirement to categorize systems in this manner. However, by working with F-16 safety engineers, avionics LRUs that meet the customer's definition of life critical were defined. For mission-critical LRUs, the Air Combat Command (ACC) has developed a list entitled the Minimum Essential Subsystems List (MESL). This list was used to map ACC-defined minimum essential subsystems to F-16 avionics LRUs.

With the life critical context in mind, five avionics LRUs, shown in **Figure 4-1**, can be considered life critical. These systems are the low altitude navigation and targeting for night (LANTIRN) navigation pod, the digital flight controls system (FLCS), the HUD, the CADC, and the INS.

The LANTIRN navigation pod is used for low-altitude terrain following in both day and night conditions. This system is used to provide terrain following cues to the pilot, thus it could be considered life critical since failure of the system may cause aircraft loss. However, sufficient safeguards are built into the avionics system to circumvent this failure mode. The FLCS monitors the operation of the LANTIRN pod. In the event of pod failure, the system issues caution and warning lights for the pilot to take appropriate action. If the pilot does not take action, the FLCS issues an automatic fly-up command.

The FLCS is a quad-redundant fly-by-wire system that enables control of the aircraft. The FLCS can be deemed life critical since failure of the FLCS will cause loss of aircraft control. Inability of the FLCS to provide proper commands for control of the aircraft could occur after two simultaneous failures or after three non-simultaneous failures. Both events are highly improbable. The FLCS can be electrically powered by any of four generators or the aircraft battery.

The HUD displays altitude, airspeed, attitude, heading, and flight path information to the pilot. It receives this information from the CADC and INS. The HUD is becoming a primary reference for instrument flight. Thus the HUD, the CADC, and the INS can be considered life critical since display of incorrect data on the HUD could result in collision with the ground. Although safeguards are used in the avionics system to prevent display of incorrect data, these safeguards do not result in 100-percent protection. The pilot is still required to cross check the HUD with other flight instruments.

The mapping of the ACC's MESL to F-16 avionics LRUs is shown in **Table 4-2**. The left-hand column of the table denotes the ACC's broad definition of avionics subsystems required for mission capability. The right-hand column of the table lists F-16 avionics LRUs that provide those subsystem capabilities. The table mapping is just an approximation of the mission critical systems since Lockheed Martin Tactical Aircraft Systems (LMTAS) does not denote F-16 systems as either life or mission critical. A more accurate representation would require an analysis of the F-16 LRUs required for a particular mission profile, which is out of the scope of the AMSUCP program.

4.3 COOLING SYSTEM

The F-16 environmental control system (ECS) shown in **Figure 4-2**, combines air-conditioning and pressurization functions to provide temperature conditioning; pressure regulation for control of heating, cooling, ventilating, canopy defogging, cockpit pressurization, canopy sealing, anti-*g* suit pressurization, and fuel tank pressurization; and electronic equipment cooling. The cooling system may be bypassed by using ram-air cooling in the event of an ECS failure or other emergency such as temporary loss of engine power.

Cooling air provided to forced-air cooled equipment is distributed by a main supply source that feeds branches to various LRUs in the forward and aft equipment bay compartments. The distribution lines to equipment vary in diameter and length resulting from a combination of factors such as space, flow requirements, and routing paths. The complete routing system of cooling lines to equipment is designed to achieve the required cooling of each individual equipment without adversely affecting the aircraft system and controls.

In addition to supplying conditioned air to the avionics systems, the ECS provides unconditioned ram-air to equipment in the event of a cooling system failure as well as providing ram-air to equipment specifically designed for ram-air cooling. Under a cooling system failure scenario, having ram-air provided to the equipment allows the pilot to maintain operation for mission completion and/or safe return to base.

Table 4-2. ACC Minimum Essential Subsystems List Mapping to F-16 Avionics LRUs

ACC Minimum Essential System/Subsystem	F-16 LRUs
Flight control system	DFLCS
Flight instruments	HUD, MFDS, CADC, INS
UHF communications	UHF Radio
Identification friend/foe	Identification friend/foe
Radio/inertial navigation	Instrument landing system, INS
Global positioning system	GPS
Fire control system	FCC, FCR
Targeting pod system	LANTIRN targeting pod
Navigation pod system	LANTIRN navigation pod
Weapons delivery system	SMS
Penetration aids and electronic counter measures	ECM pod, AIBU, ARWR, CMDS

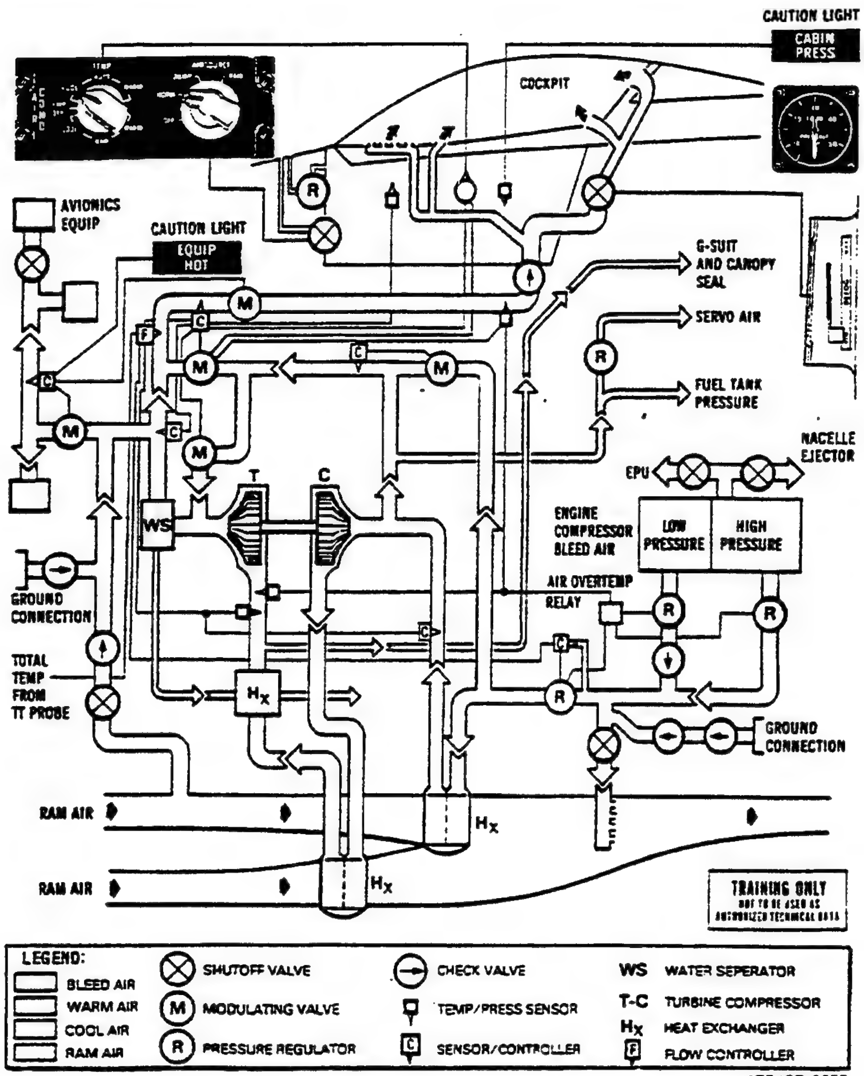


Figure 4-2. F-16 Environmental Control System

4.3.1 Air Conditioning

To perform the required temperature and pressure functions described previously, high-pressure and high temperature bleed air from the high- or low-stage ports on the engine is directed through a turbine compressor and air-to-air heat exchangers where it is cooled by ram air and routed to the appropriate areas. Conditioned air enters the cockpit on both sides, the top rear of the seat, through the angle vent on the instrument panel, and through the canopy defogger. A cockpit temperature controller receives signals from temperature sensors and from a manually operated control panel to control the cockpit temperature automatically. In the event of an ECS malfunction, emergency ram air operation can be selected via the air source switch, located in the cockpit, for ventilation and cooling. To provide cooling air to the cockpit and avionics equipment during maintenance and engine-off situations, a ground cooling cart can be connected on the lower left side of the fuselage just above the nosewheel area.

4.3.2 Pressurization

Air pressure is provided by the pressurization system for control/operation of some of the ECS, canopy seal, anti-*g* suit, fuel tanks, and radar. Pressure in the cockpit is controlled automatically according to a designed schedule. A cockpit pressure safety valve relieves pressure anytime the cockpit pressure exceeds ambient pressure by 5.4 psi. The canopy seal is inflated/deflated with the mechanical locking/unlocking of the canopy.

4.4 EQUIPMENT LOCATIONS

F-16 avionics equipment is distributed throughout the aircraft, however typical systems are located in five major areas. These areas are the forward and aft equipment bays, shown in **Figure 4-3**, and the wing station, cockpit, and remote equipment bays shown in **Figure 4-4**. The forward and aft bays house a majority of the avionics system LRUs, including the SMS, display generators for the HUD and MFDS, the radar, and the FCC.

The forward bay is located directly in front of the pilot's seat and extends to the radome. Most of the equipment in the forward bay is forced air cooled. The aft bay is located directly behind the pilot's seat and extends to the back of the canopy. Some equipment in the aft bay, such as the FCC, is forced-air cooled while other equipment in this bay is convection cooled (i.e., heat is radiated from the LRU to the compartment).

Forced-air cooled equipment generally exhibits the highest reliability because of the effects of cooling air on minimizing the influence of the surrounding environment. Generally, higher power density equipment requires forced-air cooling to maintain temperatures within IC device limits. Under a few instances "off-the-shelf" equipment (GFE or buyer furnished equipment not designed to F-16 environmental requirements) may need to be installed in a specially designed enclosure or incorporate other provisions to allow the equipment to be compatible with the F-16 installation environments. Since the equipment is not designed to the F-16 environment, if modifications are not performed then the equipment will have a higher susceptibility to the F-16 temperature environment as well as potentially reduced reliability.

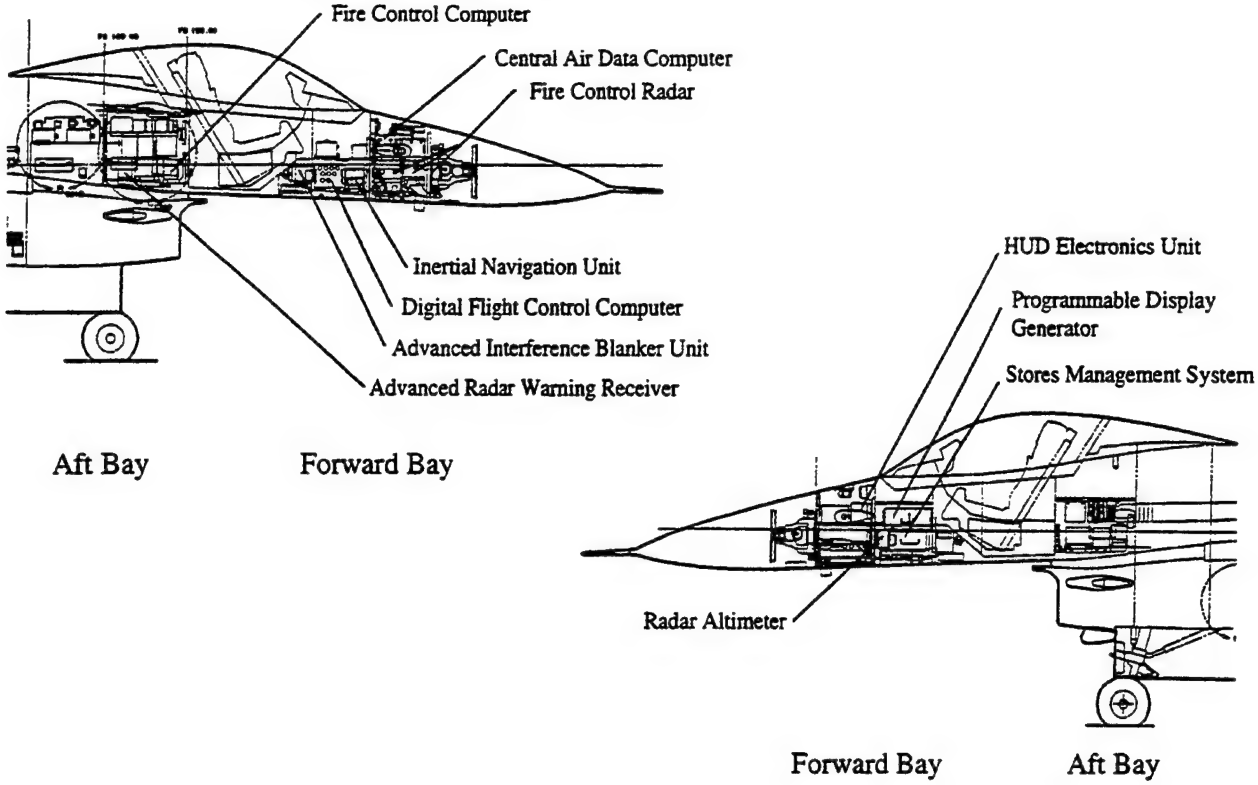


Figure 4-3. F-16 Equipment Locations (Forward and Aft Bays)

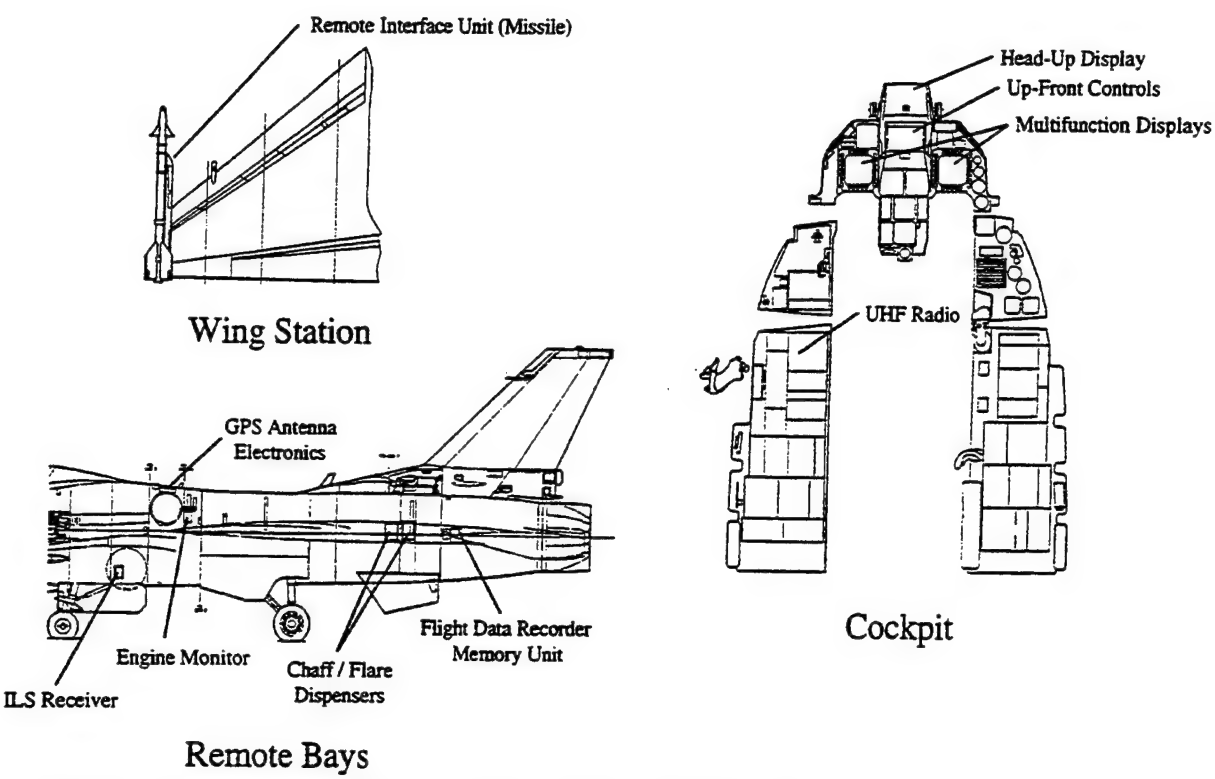


Figure 4-4. F-16 Equipment Locations (Wing Station, Remote Bays, and Cockpit)

Equipment located in the wing station area is subject to a wider range of environmental conditions because of the combination of influences from ambient conditions and air vehicle operations. The wing station avionics equipment consists primarily of weapons remote interface units (RIUs) and avionics pods. RIUs provide the interface between the weapon and the avionics buses located in the wings. Different RIUs are provided depending on the weapon type. RIUs are convection cooled within the pylon environment. Avionics pods consist of systems, such as LANTIRN. This system attaches to the centerline of the aircraft and provides either navigation or targeting functions depending on the pod used. Some pods, such as LANTIRN, provide their own internal cooling system, while other pods are convection cooled.

The crew station avionics consists of systems that interact with the pilot, such as the HUD, multifunction displays (MFDs), radios, and the up-front controls (UFC). This equipment is convection cooled within the consoles and instrument panels. The temperatures within these locations are generally higher than the local crew station environment because of the complement of equipment heat sources within these areas. In addition to equipment and metabolic heat, the crew station is subject to solar radiation influences; specifically the effects of extreme hot soak conditions at initial power-up before cool down.

Generally, the crew station equipment environment is less severe than those of other bays with the exception of the effects of solar radiation heating and material surface degradation effects. The crew station environment must allow for proper pilot-to-vehicle interface, therefore equipment surface temperatures exposed to the pilot are designed to minimize touch temperature limits. Since these exposed surfaces are somewhat isolated from internal LRU devices, the internal IC temperatures are influenced more by internal console temperatures than by the crew station local environment.

Remote bays are located in various areas on the aircraft such as:

- Near the engine for engine diagnostic units
- Near the rear of the aircraft for the chaff and flare dispensers and the flight data recorder memory unit,
- Near the engine inlet for the instrument landing system and data link
- Near the aircraft skin for antennas and antenna electronics.

In addition to the major systems identified, other miscellaneous equipment such as systems for performing fuel control, electrical power control, and warning may also be located in various remote locations. Equipment located in the remote compartments is convection cooled.

4.5 F-16 EQUIPMENT DESIGN CONSIDERATIONS

Aircraft designs vary from configuration peculiarities and the equipment complement. Thus, the environmental characteristics of the design are influenced by a combination of factors such as: peculiar installation characteristics, influence of other installed or removed heat sources, and effects of induced environments resulting from varying aircraft operational conditions. The following paragraphs provide insight into designing F-16 equipment from an environmental standpoint.

4.5.1 Forced-Air Cooling Reliance and Design Considerations

A large number of F-16 LRUs rely on forced-air cooling or some other external supplied cooling media because of higher power densities. Since these LRUs use forced-air cooling, they are less sensitive to the external

temperature environment. General information from tests on equipment indicate that IC temperatures within forced-air cooled LRUs vary within a range of 5 to 10°C as a result of design packaging features and temperature environment changes.

The majority of component temperature differences in forced-air cooled LRUs are attributed to the range in flow rates and supply air temperatures delivered to equipment during ground and inflight conditions. These temperatures can be as low as -40°C to as high as +49°C during abnormal conditions. Temperatures can also be less than -40°C during system failure. Normal delivery temperatures typically range from -20 to +10°C inflight and from +2 to +20°C during ground conditions.

IC case temperature ranges for forced air cooled designs under normal operating conditions are dependent on the specific circuit card and LRU designs, and can range from -20 to +110°C. Under abnormal conditions, such as those that may occur during emergency or failure modes and that are dependent on specific hardware requirements and design characteristics, IC temperatures can approach device limits. The design can potentially allow service conditions for the range of IC temperatures from -55 to +125°C. Specific application requirements and design tailoring may be necessary to meet peculiar IC temperature range limitations.

4.5.2 Natural Cooled Equipment Considerations

Natural-cooled avionics consist of equipment that rely on convection and radiation to the surroundings for heat transfer. Since natural-cooled equipment relies on the surroundings for heat transfer, the equipment temperatures are highly influenced by changes in the surrounding temperatures. This type of equipment has the least flexibility in terms of power dissipation levels and design characteristics (i.e., placement of circuit boards and components internal to chassis). Some designs have growth margins for increased dissipation, however they require qualification to verify performance is met at the higher operating characteristics (if changes result in a temperature increase).

Generally, designs for natural-cooled equipment require several iterations to determine the correct component placement option that satisfies all design and performance criteria. Since these designs rely significantly on the compartment surroundings for cooling, the IC temperature trends for natural-cooled avionics are higher than those of forced-air cooled designs. Generally, significant design effort may be required for natural-cooled avionics designs to achieve the IC temperature limits within the -55 to +125°C range. After performing applicable design trades to examine these and other limits within the requirements of the natural cooled design, the remaining option may be to change to a forced-air cooled avionics design. The associated problems related to cooling availability and/or aircraft required modifications need to be assessed on a case-by-case basis.

4.5.3 Remote Compartment Environment Considerations

Remote environments are influenced significantly by aircraft operations, equipment, and other heat sources, as well as climatic conditions. Depending on locations and other influences, aircraft structure surface temperatures range from -60 to -35°C for the low extremes to as high as 132°C for short transients. Compartment low temperature environments generally are between -52 to -45°C but may be as low as -54°C for extreme conditions. High temperature extremes for peculiar equipment may range as high as 90°C for 30 to 60 minutes, 104°C for 30 minutes, and 110°C for 10 minutes. Temperature extremes of the range from 110 to 132°C may result for durations less than 10 minutes; however, the characteristics are influenced by the specific installation design and associated environment.

The operational requirements, location, and heat sources are a significant consideration when dealing with remote compartments. Equipment designed to withstand transient environments may incorporate internal thermal capacitance or rely on peculiar installation provisions to minimize these influences. Some equipment may require the use of low-power devices to the greatest extent possible. These devices allow usage in these high temperature environments or other conditions than those addressed in this report. Since avionics located in these areas are of the natural-cooled design, the applicable IC temperature range for this equipment is generally within the -55 to +125°C limits.

4.5.4 Bay Compartment Conditioning

Bay compartment conditioning to limit temperatures within specifications has been implemented on some configurations requiring specific provisions. Some remote compartments incorporate these temperature limiting provisions as a result of the location and heat sources as described earlier. These provisions result in temperature conditioning occurring within a band of ±5 degrees of the 71°C specification limit. Temperatures are not controlled to be less than specification limits, since the intent is to limit extreme conditions while minimizing aircraft cooling loads. IC temperature ranges for avionics located in these areas are also within the -55 to +125°C limits because of the natural-cooled design characteristics of the equipment.

4.5.5 Future Environmental Requirements

Future avionics growth will increase compartment temperatures. These temperature increases are dependent on many factors, such as installation location, power, other equipment, and cooling allotments. Bay temperatures have steadily increased by levels that are approximately 7 to 10°C higher than early aircraft configurations. This may result in temperatures approaching the specification criteria.

The typical environmental characteristics summarized in the following sections represent F-16 specified requirements. The outcome of typical design efforts to satisfy imposed design requirements result in the avionics design temperature characteristics. Typical designs require tailoring of device placement onto circuit boards as well as tailoring of circuit board placement within the chassis housing to ensure that proper temperature and operational characteristics are met.

Since F-16 future configuration requirements are unknown, the influences on system temperature characteristics specifically with potential future upgrades and/or configurations cannot be projected at this time. In general, the design requirements imposed on the systems ranging from the temperature requirements to cooling limits as well as other environmental parameters are the dominating criteria for either a "make-it work" aircraft installation configuration or a redesign of the system if the original design requirement limits are violated. This is applicable to any design regardless of type of installation, cooling approach, or operational intent.

4.6 LRU ENVIRONMENTAL SPECIFIED REQUIREMENTS

F-16 avionics environmental requirements are specified at the LRU level. A majority of F-16 environmental requirements are based on Mil-Std-210A climactic criteria that is tailored to address peculiar F-16 compartment conditions as well as vibration characteristics. This tailoring in most cases results in F-16 environmental requirements more severe than those stated in Mil-Std-210A.

Table 4-3 shows the environmental specifications for equipment located in the four major avionics equipment locations of the F-16; the forward bay, aft bay, wing station, and cockpit. This data corresponds to the equipment minimum requirements specifications for LRUs located in the appropriate aircraft areas.

Table 4-3. F-16 Specified Environmental Data for Selected Aircraft Locations

Parameter	Forward Bay (SMS ECIU)	Aft Bay (FCC)	Wing Station (AMRIU)	Cockpit (MFD)
Vibration	0.02 - 0.025 g^2/Hz for 3 hrs; 15 to 2K Hz: gunfiring max 3.7 *gs* peak. 0.016 random	0.02 - 0.04 g^2/Hz for 1 hr: 15 to 2K Hz: gunfiring max 14 *gs* peak. 0.14 random	0.04 - 0.14 g^2/Hz for 3 hrs: 15 to 2K Hz: max -0.33 long, 4.0 lat. 0.7 vert	0.02 - 0.025 g^2/Hz for 3 hrs; 15 to 2K Hz: gunfiring max 15 *gs* peak. 0.015 random
Shock	15 *gs*, 11 ms, 1/2 Sinusoid	15 *gs*, 11 ms, 1/2 Sinusoid	15 *gs*, 11 ms (long) 40 *gs*, 40 ms (vert and lat) 1/2 Sinusoid	15 *gs*, 11 ms (basic) 40Lo/20V/15L, 11 ms (crash) 1/2 Sinusoid
Temperature (operating)	-40 to +71°C; 1.7°C/s	-40 to +71°C; 0.7°C/s	-54 to +71°C; 1.7°C/s 110°C for 10 minutes	-40 to +71°C; 1.7°C/s
Temperature (non-operating)	-54 to +95°C; 1.7°C/s	-54 to +95°C; 0.7°C/s	-54 to +110°C; 1.7°C/s	-54 to +95°C; 1.7°C/s
Temperature/altitude	-40 to +71°C; sea-level to 78K feet	-40 to +71°C; sea-level to 78K feet	N/A	-40 to +71°C; sea-level to 78K feet
Temperature shock	Cooling air -18 to 49°C/1.7°C/s	Cooling air -18 to 49°C/1.7°C/s	N/A	N/A
Humidity	Mil-E-5400	Mil-E-5400	Mil-E-5400	Mil-E-5400
Moisture	Mil-E-5400	Mil-E-5400	Mil-E-5400	Mil-E-5400
Fungus	Mil-E-5400	Mil-E-5400	Mil-E-5400	Mil-E-5400
Salt-sea atmosphere	Mil-E-5400	Mil-E-5400	Mil-E-5400	Mil-E-5400
Sand and dust	Mil-Std-210	Mil-Std-210	Mil-Std-210	Mil-E-5400
Fluids	Water or ice; JP-4,5,8 fuels; anti-icing; hydraulic; coolants; lubricating oil	Water; JP-4,5,8 fuels; anti-icing; hydraulic; coolants; lubricating oil	JP-4,5 fuels; hydraulic; coolants; lubricating oil	Water; JP-4,5,8 fuels; anti-icing; hydraulic; coolants; lubricating oil
EMI	Mil-Std-461	Mil-Std-461	Mil-Std-461	Mil-Std-461

Specified F-16 temperature requirements for equipment areas range from as low as -54 to +71°C for operating conditions with a maximum temperature change rate of 1.7°C per second and maximum limited exposure temperature of +110°C for 10 minutes. The non-operating temperatures range from -54 to + 95°C with a maximum temperature change rate of 1.7°C per second. These temperature conditions are used by equipment designers to aid in defining design features and cooling requirements to achieve proper IC temperature limits within the -54 to +125°C range or other as may be applicable to the design.

Although these are typical ranges used in specifications, tailoring for some system LRUs is accomplished to accommodate other extreme conditions as may be influenced by installation, usage, and/or heat dissipation. Thus, specifications for peculiar F-16 LRUs may vary from those specified with more stringent environmental specification requirements. In addition, any peculiar requirements dealing with fail-safe operation for flight-critical equipment may require special emphasis to ensure the equipment maintains proper performance during extreme environment scenarios.

A majority of USAF aircraft life occurs during peace time scenarios. These peacetime scenarios (as well as flight test scenarios) are benign when compared to war environment usage scenarios. During wartime scenarios, aircraft limits may be exceeded on the basis of customer operations outside contractual design specifications. In addition, environmental conditions tend to approach specifications and under some instances may be beyond specifications because of customer operations outside air vehicle operations. Reliance on benign environments for design should be avoided.

Specific requirements to accommodate peculiar installations dealing with high temperature and/or flight safety may require tailoring of the specified requirements. In a majority of cases, equipment design requirements allow the flexibility for relocation of equipment to different equipment bays if necessary to accommodate aircraft changes and upgrades. If equipment designs are tailored to specific locations, extra effort to accommodate these avionics at other potential locations may result in additional aircraft changes and/or redesign of equipment.

In addition, aircraft compartment environments are generally limited to be within the range limits specified and are not controlled to be less benign than specified. For some isolated bays, a temperature limit control is included to accommodate the influences of many heat sources. This control is designed specifically to provide temperature conditioning within the limits of either Mil-E-5400 Class 2 or F-16 requirements.

Temperature conditioning to anything other than these limits is not accomplished by design. This allows minimizing the aircraft cooling load while limiting compartment temperature limits to within design requirements. Under some environmental combinations, heat sources, and other induced influences, the equipment will be exposed to the specified design requirements. With added heat loads and/or relocated equipment for new aircraft configuration designs and/or upgrades, efforts are made to maintain equipment bay temperatures within equipment temperature requirements.

4.7 IC DEVICE OPERATIONAL CONSIDERATIONS

Operating temperature characteristics of equipment are dependent on many factors present and future. Equipment temperature characteristics under any and all operating scenarios, aircraft configurations, operating modes, and interactions of other influences is a monumental task, which is out of the scope of this study. However, the intent is to provide information on the typical operating characteristics and trends of equipment containing ICs that are located at different aircraft locations typical of present configurations and peacetime scenarios. It is not intended to present scenarios for situations of emergency, wartime, or failure modes that will result in different temperature characteristics.

IC temperatures are dependent on both packaging requirements and cooling air allotments. Use of commercial ICs in equipment should be based on the packaging constraints to use flow rate allotments no greater than that shown in **Figure 4-5** while subjected to environments similar to those defined in **Table 4-3**. **Figure 4-5** represents the characteristics for airflow delivery as a function of supply temperature. The flow allotments for the equipment are dependent on design requirements and may range between 88 to 100 percent of the range shown in **Figure 4-5**.

The range of component case temperatures measured within this allotment typically fall between 68 to 107°C under extreme conditions and power dissipations resulting in junction temperatures that are 2 to 15°C higher. Depending on the device type and circuit card packaging, some aircraft LRUs (i.e., radar, ECM) have devices with case and junction temperatures higher than those shown here. General environment influenced trends indicate that a 30 to 50°C change in the external environment results in only a 5 to 10°C IC temperature change for forced-air-cooled designs.

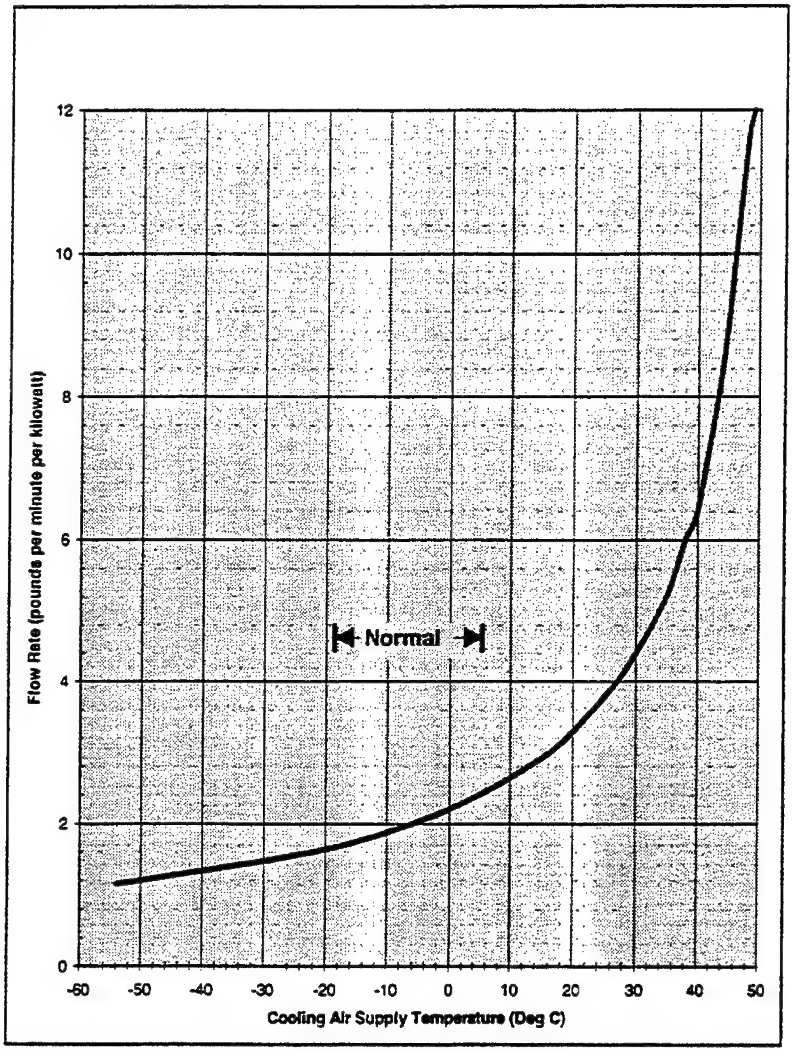


Figure 4-5. Avionics System Cooling Allotment

Typical operating design characteristics of systems designed to meet requirements similar to those specified in **Table 4-3** are summarized and presented in **Table 4-4**. This information is based on the outcome of some designs that are either forced-air cooled or natural-cooled (free convection design) LRUs. It should be noted that these characteristics represent typical usage ranges and may not represent design extremes required to meet all aircraft design scenarios. The low and high temperature ranges summarized represent the typical range of case temperatures for ICs as influenced by cold or hot conditions for the specific aircraft location.

Power-up temperatures represent the initial conditions at application of power to the equipment that occur on the ground either during cold conditions (i.e., Alaska, Great Falls Montana, etc.) or during hot conditions (i.e., hot desert regions). An exception to ground start at cold conditions is applicable to some wing station equipment that is only powered-up in flight unless ground checkout is being accomplished.

Table 4-4. Avionics IC Case Temperature Trends for LRUs at Selected F-16 Aircraft Locations (Nominal Operating Conditions not Representative of Possible Extremes)

Aircraft Location	Temperature Parameter[1]	Power-Up[4] Temperatures (°C)		Ground Conditions (°C)		Inflight Conditions (°C)	
		Initial	Peak	Low[2]	High[3]	Low[2]	High[3]
Forward equipment bay[5]	IC low	-40	N/A	-23	+69	+37	+73
	IC high	+75	+86	-3	+87	+58	+92
Aft equipment bay[5]	IC low	-40	N/A	-32	+54	+42	+66
	IC high	+68	N/A	+12	+90	+65	+97
Wing station bay	IC low	-50	-48	-35	+48	-42	+86
	IC high	+93	+96	-16	+67	+10	+104
Cockpit location	IC low	-40	N/A	-12	+76	+15	+51
	IC high	+95	+104	+15	+101	+42	+78
Remote compartment	IC low	- 40	N/A	-29	+79	-37	+79
	IC high	+77	N/A	-11	+92	+16	+98

Notes:

1. IC case temperatures are based on typical F-16 designs using equipment design and test characteristics factored for F-16 operations and nominal basing conditions. Temperature parameters represent a range of integrated circuit device case temperatures from low to high of typical LRUs located in various compartments.
2. Low temperatures are representative of a combination of day conditions that vary between polar and extreme cold conditions.
3. High temperatures are representative of hot day Mil-Std-210A conditions.
4. Power-up temperatures are applicable to initial application of power typically occurring during ground conditions with exception to wing station bay, which represents inflight power-up. Power-up temperatures of wing station equipment on the ground would be -40°C.
5. Forward equipment and aft equipment bay conditions are representative of forced-air designs.

Cockpit power-up for high temperature conditions represent initial application of power following opening of the canopy under hot soak conditions. Under this condition, power may be applied to the equipment before complete cool down of the crew station resulting in temporary high peak temperatures from added equipment heating. Non-operating cockpit temperatures resulting from closed canopy and solar heating have been determined to reach 93 to 94°C. With application of power, the equipment temporarily achieves temperatures higher than 95°C.

Ground conditions represent the ranges experienced either during normal operation or checkout scenarios with aircraft or external cooling provided. The highest crew station equipment temperatures are experienced during ground checkout activities with the canopy open, solar radiation, and equipment heating. Inflight conditions represent the most benign conditions for crew station equipment, whereas for equipment located in other compartments the inflight conditions may be the more severe for temperature environments.

Since all equipment has been designed to meet specific requirements, which may consider worst-case operational modes and/or environments, the outcome on design characteristics has resulted from many trades on design features, cooling method, parts placement, and parts selection. In addition, during qualification phases for the equipment, the performance characteristics have been verified to meet requirements or in some instances have influenced circuit design or part changes resulting from the exposed temperature, humidity, or vibration influences. In the event of deviation from current design requirements, trade studies are required to assess the potential risk on the specific designs to determine changes or impacts at the aircraft level or LRU level. These trades consider all aspects of performance and safety and include aircraft failure modes and operational extremes.

4.7.1 IC Normal Versus Extreme Characteristics

Equipment IC operating temperature characteristics are dependent on the hardware design features, the electrical operating mode characteristics, and the cooling conditions to which the equipment is subjected. Coupled with the basic design characteristics are the extreme environments, influenced by either aircraft conditions or a combination of aircraft conditions, and increased heat internal to the equipment. This increased heat may be a direct result of added growth to avionics.

In some instances present equipment may be designed to requirements for reserved internal growth. This results in the potential for additional heat and increased temperatures from present designs. Additional or spare card slots may be made available to accommodate growth for future functions, memory, processing, or power supply conditioning. IC temperature characteristics of present designs with this growth implementation are unknown, but the general trend is toward increased temperatures.

Other influences on temperature variations from normal conditions include emergency, wartime, or failure-mode situations. Emergency or failure-mode situations may require forced-air-cooled designs to withstand conditions of reduced or total loss of cooling. This could result in temperatures varying outside the normal range.

Other situations pertaining to extreme conditions are a result of increased temperatures resulting from additional equipment integrated into the aircraft and/or higher temperature conditions as influenced by extreme aircraft operating conditions. Conditions resulting from extreme aircraft operations are more commonly experienced

during wartime. In high heat compartments, such as engine locations or areas of high power equipment, high temperatures may dominate a high percentage of the time.

Low temperature extremes are typically experienced at high altitude conditions, whereas the low altitude or ground low temperature conditions are typically experienced during severe weather conditions or regions of cold climate. Equipment most susceptible to cold temperatures is generally low power equipment located in isolated compartments.

The normal versus extreme variation in IC temperature conditions is influenced by many factors. Avionics equipment requirements are based on a combination of considerations. The design approach is highly dependent on the proper consideration of complexity, reliability, risk, and cost. The applicable avionics design functional requirements dictate the design limits to which operational performance and/or survival must be accomplished.

Present avionics designs have been tailored using military standard components. Significant efforts by equipment designers have been required in many cases to achieve temperatures that do not violate the selected IC temperature limits. Heat sink design, complexity, cooling levels, weight, aircraft modifications, and cost are directly influenced by the device temperature limits for specific applications. It should be noted that present designs have relied on the military range devices to minimize the adverse impacts of increased weight, cooling, cost, and design complexity.

New or modified designs may exhibit different characteristics on the basis of technology insertion. Continuous improvements in IC technology have resulted in reduced power levels. This results primarily from increased circuit density and reductions in circuit operating voltages. A continued trend for reduced IC voltage requirements is necessary to the meet the growing demand of ultra high processing speeds. It is the secondary effect of these results that benefit the majority of devices exclusive of processor devices. The outcome on greater than 90 percent of devices is reduced power and temperature.

A reduction in device temperature characteristics may also reduce IC temperature range requirements. Other factors, such as environmental conditions still apply; however, the associated impacts at the IC level are reduced.

4.8 CRITERIA FOR IC DEVICE IMPLEMENTATION

Table 4-5 lists potential risk levels associated with the insertion of reduced IC temperature range components into current designs if assuming a 100-percent utilization. This table lists only possible risk levels, since comparisons for all avionics operated under different scenarios and environmental conditions are out of the scope of this study. The factors of redesign within present avionics LRUs or possible benefits associated with the insertion of new ICs into existing designs cannot be compared or evaluated without proper assessment on the particular design. The associated risks may be reduced on the basis of power reductions and specific implementation areas.

Table 4-5. IC Temperature Rating Limit Risks. Comparisons of Potential Risk for Current F-16 Aircraft Locations Assuming 100-Percent Implementation.

Aircraft Location	Temperature Parameter	Normal Operations Risk (°C)			Extreme Operations Risk (°C)		
		Low	Mod	High	Low	Mod	High
Forward equipment bay	IC min limit	-4	>-40	>-35	-40	>-40	>-35
	IC max limit	+115	<+105	<+100	+125	<+115	<+110
Aft equipment bay	IC min limit	-40	>-40	>-35	-40	>-40	>-35
	IC max limit	+115	<+105	<+100	+125	<+115	<+110
Wing station bay	IC min limit	-55	>-50	>-45	-55	>-50	>-45
	IC max limit	+115	<+110	<+105	+125	<+120	<+115
Cockpit location	IC min limit	-40	>-40	>-35	-40	>-40	>-35
	IC max limit	+115	<+110	<+105	+125	<+115	<+110
Remote compartment	IC min limit	-55	>-50	>-40	-55	>-50	>-50
	IC max limit	+115	<+110	<+105	+125	<+120	<+115

Specific candidate device characteristics for replacement on present LRU circuit cards have not been identified nor the characteristics for potential alternate devices for implementation determined since it is beyond the scope to this study. The use of reduced temperature range devices is being emphasized since a good percentage of ICs may be replaced with commercial- or industrial-grade devices. It should be noted that the 100-percent solution cannot be accommodated without some risk or modification to present designs. **Table 4-5** provides a relative indicator of the risk level associated with different locations for present designs assuming a 100-percent implementation of reduced temperature range devices.

When considering the actual design implementation, several IC selection options for a specific design may exist. However, the characteristics of the actual design with the specific device need to be known or evaluated to aid in determining selection alternatives. The trends associated with the extent of redesign or implementation risk when using reduced temperature range devices can be evaluated on the basis of the available device temperature range and the extent of implementation. **Figure 4-6** shows this general trend for potential risk based on percentage of implementation required and the extent of redesign needed.

Since a single LRU is comprised of a significant number of devices operating at different power and temperature characteristics, the probabilities are low that one specific temperature range device can be used in LRUs at every conceivable location and operating environment. The probability is much higher for a single LRU that one temperature range may be adequate to accommodate greater than 50 percent of the devices.

The implementation trades may consider a high risk approach, with minimal to no redesign using low temperature range devices, or some reduced risk approach using extended temperature range devices and minimal redesign. Another option is significant redesign to minimize risk for a "make it work" approach using low temperature range devices.

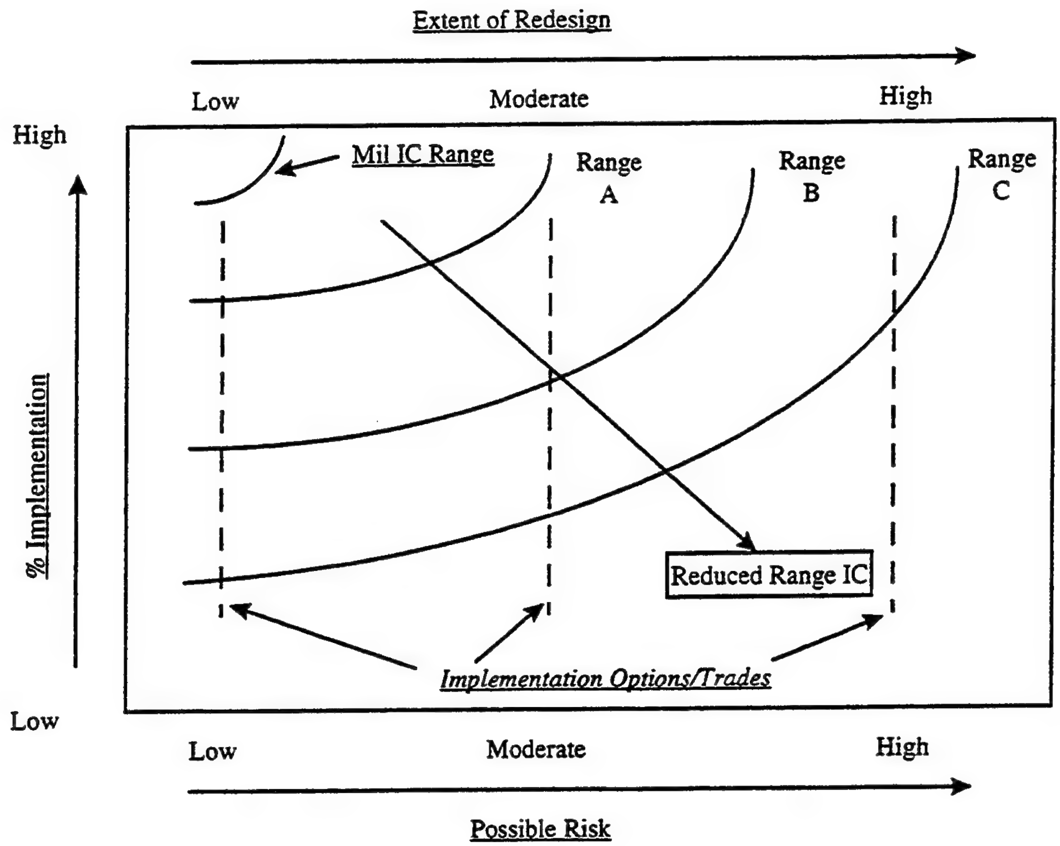


Figure 4-6. Implementation Considerations

The selection trades can only be done on a case-by-case basis. Since, internal to the avionics LRU, many device types exhibit different operational requirements based on the function as well as implementation approach, the trades on performance versus temperature range requirements need to be determined based on the specific device(s) selected. In some specific cases, functional performance variations may be directly influenced by the temperature tolerances, whereas for other cases temperature tolerances may be of no issue other than device reliability at or outside a specified temperature limit.

To simply attempt a single "plug in" approach across a broad band of designs exhibiting different characteristics and functions is risky and potentially quite costly. Without proper IC performance variation considerations, significant system performance impacts can result. These impacts can result in system functional degradation, reduced system reliability, and increased operating costs from additional maintenance.

4.8.1 Trade Considerations for IC Device Selection

Implementation of a specific IC into a design requires thermal evaluation, design trades, and testing to determine the optimum solution for the configuration. The final outcome of the temperature range characteristics for the implemented design will determine the functional and reliability performance of the system. Without available IC device operating parameter and temperature characteristic data, including

integrated functional effects within the hardware, it is difficult to determine the acceptable limits of any parameter nor the level of risk for the design.

Assuming that the parameters of the device are well known and that the functional characteristics of the circuit for a range of temperature conditions are understood, the remaining unknown is the operating temperature of the specific device when installed and operated within the LRU. It should be noted that the temperature of the device is not only influenced by its own power characteristics but also by all other devices in the vicinity that also contribute heat. Areas for future consideration in reduced IC temperature range trade studies are listed in **Table 4-6**. The shaded regions in the table show temperature ranges and risk levels for candidate study options.

Table 4-6. IC Temperature Range Trades Without Benefits of Significant Redesign—Possible Selections for Evaluation. (Note: Actual range implementation requires an evaluation of the specific design)

		Minimal Redesign			Minimal Redesign		
		Normal Operations Risk (°C)			Extreme Operations Risk (°C)		
Aircraft Location	Temperature Parameter	Low	Mod	High	Low	Mod	High
Forward equipment bay	IC min limit	-40	>-40	>-35	-40	>-40	>-35
	IC max limit	+115	<+105	<+100	+125	<+115	<+110
Aft equipment bay	IC min limit	-40	>-40	>-35	-40	>-40	>-35
	IC max limit	+115	<+105	<+100	+125	<+115	<+110
Wing station bay	IC min limit	-55	>-50	>-45	-55	>-50	>-45
	IC max limit	+115	<+110	<+105	+125	<+120	<+115
Cockpit location	IC min limit	-40	>-40	>-35	-40	>-40	>-35
	IC max limit	+115	<+110	<+105	+125	<+115	<+110
Remote compartment	IC min limit	-55	>-50	>-40	-55	>-50	>-50
	IC max limit	+115	<+110	<+105	+125	<+120	<+115

Temperature levels within the shaded regions represent candidate IC temperature ranges considered for present designs without the benefit of LRU redesign or IC reduced power effects. It is emphasized that the actual IC temperature range can only be defined when the specific IC characteristics for a selected avionics LRU are determined. The extent of implementation for an unknown device can not be evaluated since a device type may be either a single or multipurpose use device (i.e., memory versus operational amplifier). The device may therefore be isolated to either a few specific locations or many different locations within an LRU. Accommodating a reduced temperature range device type at every conceivable location without some redesign to achieve required results is not realistic. Some assessments for design and performance considerations need to be made to determine the best solution.

4.8.2 Specific Implementation Study Options

Specific avionics LRUs have not been identified nor have they been evaluated as candidates for implementation under this study. Thus, recommendations for specific reduced temperature range ICs cannot be made. Realistic options to consider in further studies are listed in **Table 4-7**. The three shaded areas of this table show the temperatures for specific areas where redesign could have the most benefit.

Table 4-7. IC Temperature Range Trades with Some Assumed Benefit Of Redesign—Possible Selections for Evaluation. (Note: actual range implementation requires evaluation of specific design)

Aircraft Location	Temperature Parameter	Some Redesign Benefit Normal Operations Risk (°C)			Some Redesign Benefit Extreme Operations Risk (°C)		
		Low	Mod	High	Low	Mod	High
Forward equipment bay	IC min limit IC max limit	-40 +110	>-40 +105			>-40 +110	>-35 <+105
Aft equipment bay	IC min limit IC max limit	-40 +110	>-40 +105			>-40 +110	>-35 <+105
Wing station bay	IC min limit IC max limit		>-50 +110	>-45 <+105			
Cockpit location	IC min limit IC max limit		>-40 +110	>-35 <+105		>-40 +110	>-35 <+105
Remote compartment	IC min limit IC max limit		>-50 +110	>-40 <+105			

The benefits of actual redesign could allow improvement from these risk levels and/or ranges and are subject to change pending actual design evaluations. The intent is to show possible implementation ranges, which are highly dependent on the actual hardware design and IC characteristics. The basis is a starting point for further study with the intent to reduce the risk level by focusing on the actual features and benefits of the design implementation changes.

Risk can be reduced through the reduction in IC power levels. The percentage of planned implementation is also another contributor to risk similar to that as depicted in **Figure 4-6**. The number of devices considered for implementation into present designs will determine the design options available at the card locations within an LRU. The risk level is therefore a function of the extent of implementation. Replacement options specific to a design potentially can allow ranges other than those identified in this study; however, the specific device and LRU application need to be known to support selection alternatives decisions.

4.8.3 Other Military Environment Considerations on IC Implementation

During the equipment life span, which is approximately 20 years, the environments and stresses induced on the avionics will be cyclic in nature. Out of approximately 8,000 flight hours, the equipment may experience as

much as 5,000 power cycles. Ground operations such as checkout and maintenance may subject the equipment to as high as 3,500 operational hours with 1,500 to 2,500 induced power cycles.

The varying levels of stress on the equipment are highly dependent on several factors including power levels, environments, temperature differences, and thermal rise extremes. Although operational time may be 1.5 to 2.0 hours per mission, it is during the operation and power cycles that the most significant thermal stresses may occur. These factors are also a consideration for present designs when planning modifications, insertion of new circuit cards, and/or integration of new components.

Without excluding all the many other influences on equipment life, the associated impacts of any design change require thorough consideration and evaluation of the type of implementation for new devices, materials, manufacturing processes, repair processes, and maintenance efforts. The military environments inclusive of humidity, fluids, dust, corrosion, as well as temperature need also to be considered. Periodic or extended exposure to different combinations of environments, including cyclic effects such as temperature and humidity, influence the varying levels of equipment life span from design to design.

4.9 CONCLUSIONS

Present avionics designs have been tailored to the installation, environment, power, and components available for the design. Modifications to these designs require assessment to determine the adverse impacts as well as benefits of peculiar modifications. Although the information presented in this report provides guidelines as well as some characteristic trends of current avionics, it should be noted that design or component changes may change these existing characteristics. It is the associated change in characteristics that needs further evaluation of the considerations summarized in this report.

As addressed previously, the technology insertion benefits associated with reduced power temperature devices are a significant factor in allowing the use of alternate temperature range components. Although not all devices within present designs may exhibit temperature characteristics at the full limits of the device, IC temperature range has a significant contribution to design considerations that include performance, weight, aircraft impact, and cost. The key to successful implementation is to recognize that some tailoring may be required on a case-by-case basis with proper consideration given to all aspects including IC type, temperature range characteristics, and intended use. When the applicable implementation options are properly considered, the maximum benefits of lowest achievable cost to gain an optimized solution will be attained.

SECTION 5
SYSTEM RELIABILITY FOCUS

The study of F-16 Block-50 avionics suggested the thermal management of the system (space and cooling) is key to total avionics system cost. The measured F-16 data indicated that -40 to +105°C is the nominal IC case temperature range experienced in most avionics locations of the existing Block-50 configuration under the nominal operating conditions. An independent worst-case temperature study on USAF bases was also conducted to assess the aircraft skin temperatures inflight via a statistical temperature ambient. The study results support the nominal measurements taken for the F-16 avionics. These nominal conditions are the optimal avionics design baseline, since it is impractical and cost prohibitive to design systems to operate at the most extreme environmental conditions. Often through robust design and possible re-configuration of avionics compartments (locations) it is possible to mitigate extreme condition and potential out-of-spec operation risks (i.e., wartime).

An effective system reliability (i.e., F-16 thermal qualifications) focus is the key to achieving the expected mission reliability and safety via the validation of the system design and component performance. In the case of the F-16 avionics application, all avionics considered to be life-critical would dictate design and validation priorities to ensure the system safety and robust performance. Effective system validations can enhance the system's robustness further by eliminating marginal components and designs before any full-rate production process. This section outlines a design environmental and performance assurance process that builds system reliability confidence regardless of military or commercial components being used.

5.1 INTRODUCTION

Figure 5-1 shows a high level summary of the design process that has been successfully followed during the development of military systems. While this process will not be fully discussed, this paper will focus on the differences as the military industry transitions from usage of Mil-Spec components to the employment of industrial- or commercial-grade parts. This sound, proven design process, which has been used for past military systems, provides customers and system users with confidence that even after changing part types, the resultant system will satisfy their needs. Conversely, through adherence to a proven design process, the product design team will develop confidence that the requirements can be met with the components selected. The results from the design process will also provide risk mitigation for the use of industrial- and commercial-grade components in future systems. Through the utilization of this process, the derived system will satisfy the quality and reliability requirements as well as meet the affordability goals that many customers have established.

Therefore, the design processes that were important for ensuring military products meet the customer's requirements are still important as the military contractors streamline from the "required design processes" to the "best commercial practices and processes." This section will provide a high level review of the process with a focus on how to use industrial and commercial components successfully in a military system.

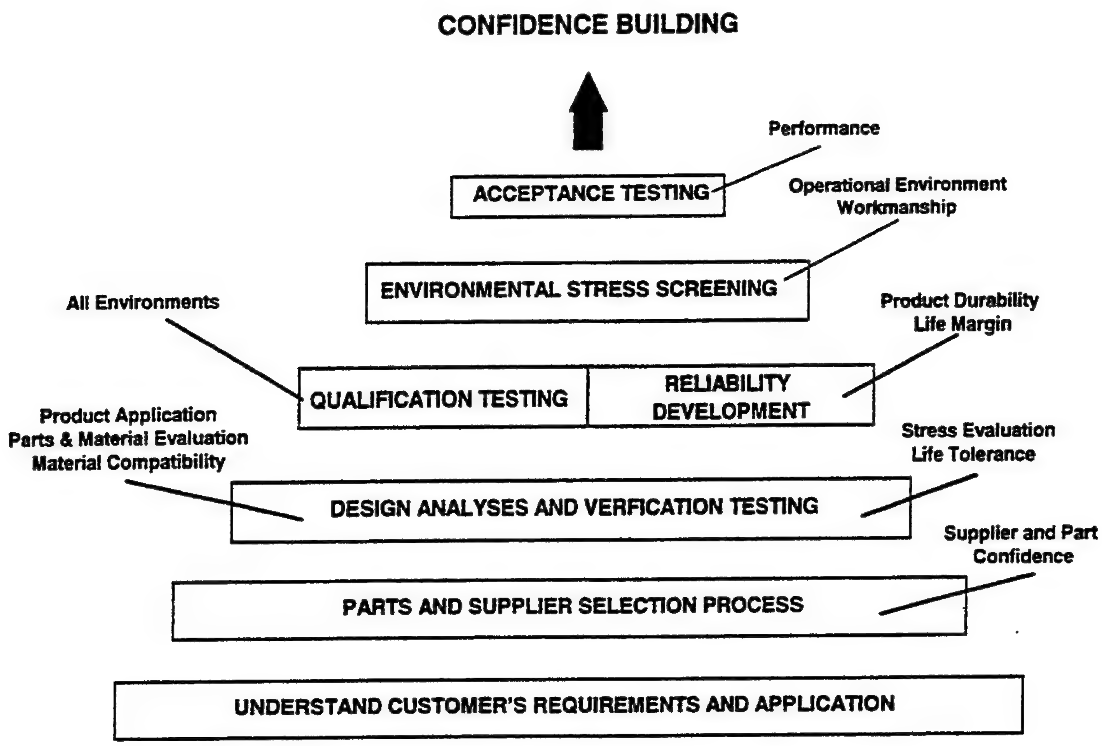


Figure 5-1. The design environmental/performance assurance process pyramid builds confidence during the system design and development.

5.2 UNDERSTANDING THE CUSTOMER REQUIREMENTS.

In **Figure 5-1**, the bottom of the pyramid emphasizes understanding the customer requirements. Today's streamlined military procurement approach is directed toward performance and key "care-abouts" without the traditional adherence to regulations; specifications and standards; and the required testing, procedures, and evaluations. Recent Request for Proposals from military customers have focused upon derivation of plans, schedules, and cost of meeting system requirements without adherence to military specification language, which only specialty groups may have understood in the past. By working with customer representatives within an integrated product team, the key specification parameters can be derived and comprehended. Essential for the product designers is to understand the environmental aspects of the system fully because these requirements will flow down into the subsystem and components that comprise the system.

5.3 PARTS SELECTION AND SUPPLIER SELECTION

The next step in the illustrated process is not new. The military supplier has always sought the best parts and suppliers that could perform the system task at hand. However, parts selection was generally limited to components that had detailed military specifications with accompanying procedural methods and testing. Furthermore, the product design constructed entirely with military parts were often inflexible to change even when requirement needs changed and more affordable components were available. The new procurement process has placed the burden of parts selection on the product developer, which can remove these non-value added steps effectively. Now the equipment supplier is responsible for supplying systems that meet the

customer's performance based requirements. The military supplier relies on a unique parts selection system to sort through the available military-, industrial-, and commercial-grade components to determine which component suppliers can best meet the necessary performance. To meet the affordability constraints imposed by many customers, commercial- and industrial-grade parts can now be selected, whereas they were previously not allowed in military systems. The growth in the non-military IC market (non-military parts comprise 99 percent of the $100 billion semiconductor market) is concurrent with significant improvement in component reliability during the last decade. Commercial ICs, while significantly more affordable than military-grade ICs, now equal the military parts in reliability and have other advantages that can result in increasingly affordable military systems.

Achieving the lowest total cost of ownership while using "best commercial practices" consists of selecting reliable parts from best-in-class part suppliers. The following paragraphs offer suggestions in the selection of quality components and suppliers.

5.3.1 Standardize and Minimize

Device standardization and supplier selection are important factors in reducing the risk and raising the comfort factors during the conversion to non-military microcircuits. The list of suppliers used during the conversion to non-military microcircuits is usually developed based upon experience with the existing supplier base. Consider the following key items when selecting suppliers:

- Equipment manufacturers and component suppliers continue to reduce their supplier and customer bases
- Select suppliers that recognized industry leaders in specific commodities
- Pick as few suppliers as possible to minimize the level of resources required to maintain a good relationship.

5.3.2 Take Advantage of Historical Relationships

- Take advantage of the historical supplier relationships. The supplier relationship will most likely change when you move to non-military parts
- Reuse components that achieve system requirements when they are used in other applications that are similar
- Processing components in accordance with the Qualified Manufacturers List (QML) is the military semiconductor industry approach to using best practices while removing non-value added processing from military components. Take advantage of existing relationships with QML suppliers. QML components have continued to be used successfully in military systems and should continue to be considered for future applications. The applicable QMLs for microcircuits are Mil-Prf-38534 (hybrid) and Mil-Prf-38535 (monolithic).

5.3.3 Review Suppliers in Detail When There is No Prior Experience

Networking within the industry and through third parties can provide insight into which suppliers have been used successfully in similar applications. Assess and rank the following items to develop a criteria that best meets the organization's goals of cost, performance, quality, and reliability:

- Assess product quality, obtained from the suppliers internal testing
- Implement incoming inspection as appropriate. This may consist of electrical re-verification, reliability screens (such as, burn-in, PIND testing, sample testing destructive tests such as HAST or 85/85), quality assessments (such as, PIND testing, solderability tests, DPA, C-SAM), and administrative actions (such as, correct part, marking, packaging, paperwork). It should be noted that most suppliers believe that redundant testing by the customer can lead to over-stressing parts and degraded the reliability.
- Review the need for any special processing (such as, tape and reel, electrical screens, added burn-in, lead forming, modification to standard lead finish, reliability screens).
- Understand failure mechanisms and identify failure analysis capabilities
- Assess the supplier's use of statistical process controls (SPC)
- Reliability monitoring program
- Survey the supplier's facilities if necessary and other means of verification are not available (such as, third-party audits)
- Review suppliers product release qualification testing (initial release and product or process changes)
- Understand the suppliers process change control and notification system
- Review the supplier's processes for vendor/subcontractor control.
- Internal audit results (if available).

5.3.4 Team With the "On-Line" Suppliers and Improve the Business

Once a supplier has been designated as "preferred," a team consisting of members from both the equipment manufacturer and supplier need to address each others concerns and continue to improve communication between companies. The focus of this team is to improve the business relationship between the two parties. The equipment manufacturer is driven by using products that meet performance requirements (both short term performance as well as long term) at the lowest total cost of ownership. The supplier is driven by supplying products with sufficiently high return on investment (facility, personnel, and consumable items) while still meeting long range strategic goals (financial, technical, and market). This team should focus on the following metrics:

- On-time delivery
- Quality
- Responsiveness
- Continue to reassess the items that were used to initially bring the supplier on-line and make sure that the assumptions continue to support today's existing market requirements.

5.3.5 Review Distribution as a Viable Source

The level of activity with distribution has continued to grow as suppliers handle fewer direct accounts. This has prepared many military equipment manufacturers for sourcing from distributors. A strategy for working with distributors should include the following activities:

- Be proactive, use distributors as additional resources to obtain supplier information
- Distributors can lower the level of activity the equipment manufacturer needs to expend because several suppliers can be addressed by a single distributor

- Distributors can provide information on unfamiliar suppliers, such as those suppliers not on the preferred supplier list
- Leverage distributors for the value-added they provide:
  - Lower minimum procurements
  - Shorter delivery cycles than most manufacturers
  - Tape and reeled components
  - Programming, pre-tinning.

5.3.6 Selecting the Right Component

- Availability of product to reduce engineering design cycle time
- Availability of simulation and design models (electrical and physical) is a major factor in design cycle time
- Availability of inventory is a factor in rapid prototyping cycle time
- Use of in-house recommended parts allows the equipment manufacturer to leverage resources, knowledge, and volume across several programs
- Listen to what the suppliers recommend. Suppliers can guide the equipment manufacturer with recommendations for component availability (short and long term), pricing, performance, and constraints.

5.4 DESIGN ANALYSES AND VERIFICATION TESTING

Design analyses and verification testing are key to ensure that system requirements are satisfied. The following design analysis techniques are good design practices to ensure that requirements are satisfied:

- Use of stress derating
- Design simplification
- Standard components and circuits
- Transient and overstress protection
- Parameter change analysis
- Worst-case analysis
- Parts/circuits tolerance analysis
- Junction temperature evaluation.

Also, the following techniques are necessary within the design process:

- Internal and external environmental control (designing for the environment, temperature protection, shock and vibration protection, moisture protection, sand and dust protection, explosive proofing, electromagnetic radiation protection, etc.)
- Failure-tolerant design techniques
- Safety margin for non-electronics parts
- Exclusion of any design features or parts that have created reliability problems in previous equipment (lessons learned).

Often considerations for industrial and commercial grade parts, which are available in plastic encapsulated packages, necessitate special models for thermal analysis and for other design modeling. Some component

testing to confirm compliance may also be necessary to verify the capabilities of parts within the application. These analyses, as necessary for the system application, can be used to minimize risk when using commercial parts. As a result of these analyses, design iterations may be required to attain full performance requirements within the application.

5.5 QUALIFICATION TESTING AND RELIABILITY DEVELOPMENT

Testing the system design against the customer requirements is the next step. Qualification usually encompasses the ability of the system to perform within—and to survive—the individual environments anticipated for the equipment. Some examples of qualification tests are shock, vibration, temperature extremes, EMI, and many others. Reliability testing is usually associated with operating within specifications over the intended service life with a specified reliability goal in mind. Although reliability tests range from expensive statistical measures to a few developmental units seeking out system weaknesses, the usual process consists of determining failure causes and subsequent corrective actions. The result ensures minimum product returns from the customer and therefore maintain customer satisfaction with the product.

5.6 ENVIRONMENTAL STRESS SCREENING AND ACCEPTANCE TESTING

As shown in **Figure 5-1**, confidence in the military product increases as each step in the process is achieved successfully. The remaining stages are to ensure the product meets performance parameters after an ESS of vibration and temperature. The temperature range in ESS will ensure that the product meets the temperature extremes for the product regardless of the specification limits of the individual components used therein. The HALT/HAST approaches used recently have increased field reliability via assessment of robustness when the system is exercised over extreme environments. These findings can show weaknesses and eventually provide higher product capability and user reliability.

5.7 CONFIDENCE IN THE END ITEM

The previous design process provides confidence that the end item product will perform as required. This process is vital to ensure the user there is little or no risk associated with the use of commercial components. The risk of commercial parts meeting the expectations of the user lies with the supplier of the product. Therefore, those product suppliers that practice best commercial practices will do those tasks necessary to achieve product requirements with minimum risk. These suppliers work diligently to avoid customer dissatisfaction and the cost associated with field returns. Those product suppliers that have not implemented sound design practices will simply not survive in today's marketplace.

SECTION 6
PEM IMPLEMENTATION FRAMEWORK

In today's shrinking military market, it is neither feasible nor affordable to ensure a continuous supply of military ICs to meet long-term DoD procurement needs. The DoD focus on affordability and commercialization in the recent years begin a new trend in product obsolescence and divestment in the military IC industry. The marketplace has changed dramatically reflecting the on-going decline of the U.S. defense budget in a post-cold-war era.

To deal with this change effectively, DoD mandated the Acquisition and Mil-Spec Reforms to eliminate barriers and to drive system affordability through the adoption of best commercial practices (BCP). DoD also anticipated that a culture change was necessary for all the military stakeholders to cope effectively with the paradigm shift. Through DoD leadership, the once rigid and inspection-oriented business environment has begun its integration with the mass commercial market and its best practices. This mass market, which thrives on self-improvement without rigid external control in an environment of change and risk-taking, is primarily driven by volume and cost competitiveness.

The PEM implementation framework, shown in **Figure 6-1**, entails a four-step transformation process to achieve affordable and reliable military systems through optimization of today's PEM capability and supplier quality processes. **Figure 6-1** illustrates this proposed framework where each of the four stages (discussed in detail in Subsections 6.1 to 6.4) is three-dimensionally inter-linked with its environments (DoD, BCP, and OEM's implementation/risk mitigation emphasis) after entering (signified by the green arrows) a commercialization gateway. This gateway signifies the beginning of a new paradigm (i.e., commercialization) for today's military stakeholders as they progress through a culture-change process. It is a choice that is based on an organization's affordability-drive and risk-taking propensity (demeanor) to either enter the gateway or to walk-by this commercialization challenge/opportunity. Effective execution and integration of this framework within the existing processes could enhance the readiness of stakeholders to cope with "changes" and to mitigate "risks" in today's new military business environment.

A pilot study was conducted on two best-in-class linear IC suppliers as part of the research. The intent was to expand exploration into today's BCP and teaming feasibility, and to seek possible solutions to overcome the PEM application issues on extended temperatures and quality assurance. These suppliers were selected from TI System Group's strategic supplier database, and they have provided invaluable insight toward the formation of this framework and to the overall AMSUCP study.

6.1 BASIC KNOWLEDGE

This is a fundamental step for any purposeful endeavor. The basic knowledge of the PEM, BCP, and market realities is a building block for the PEM implementation process. Attainment of this knowledge base enhances one's "out-of-box" mental attitude and decision making process to excel in today's changing military market. This section encourages a focus on commercialization knowledge, but is not limited to those highlighted herein.

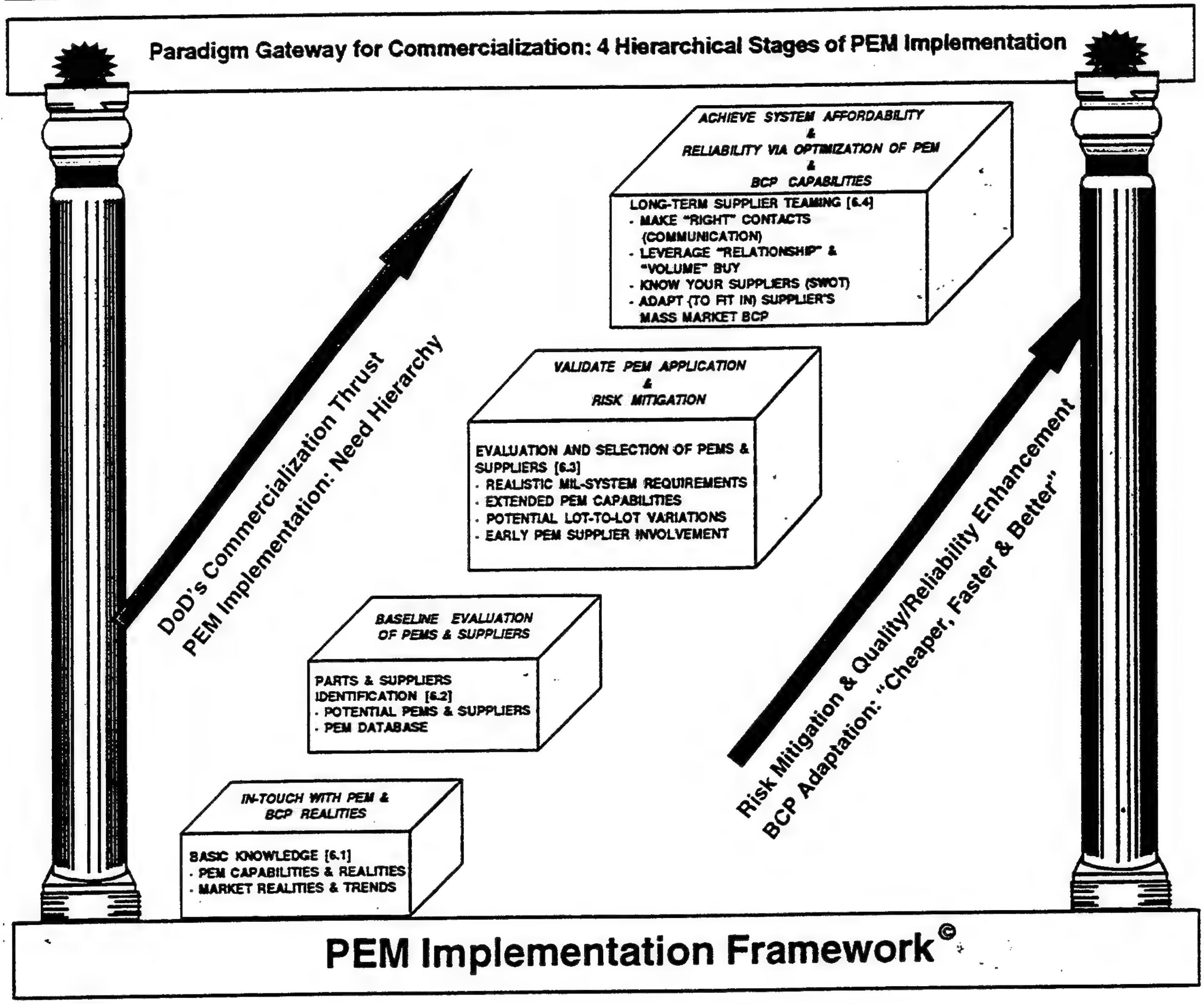


Figure 6-1. PEM Implementation Framework©

6.1.1 PEM's Capabilities

PEMs have four major advantages over their ceramic counterparts: cost, size, weight, and availability (new technologies). A savings of 40 to 70 percent in component cost is typical when procuring standard PEMs over Mil-Std-883 ceramic (hermetic) ICs. This includes ICs in various families and packaging technologies, such as DIP and SMT.

Although the physical size of ceramic and plastic DIPs is about the same, there are many more ICs offered in smaller configuration plastic packages, such as surface-mount packaged small outline integrated circuits (SOICs). Because of the inate characteristics of plastic versus ceramic, PEM weight is generally half as much as that of comparable ceramic ICs. However, the real weight advantage lies in the opportunity to use smaller

packages. Smaller components result in smaller and fewer circuit boards, interconnects, and chassis. PEMs also have the product availability advantage over ceramic in terms of more new technologies and innovative designs.

Unlike the traditional military hermetically sealed IC package, a PEM is encapsulated by a plastic molding compound that undergoes a supplier-unique proprietary packaging process. Because of the moisture permeable characteristics of the plastic, many studies have been performed to determine its long-term dormant storage reliability. Test data (via THB and moisture-life modeling) suggests that today's PEMs are capable of meeting a typical 20-year missile storage requirement. While there is still ongoing disagreement on this subject, various missile programs are currently being developed utilizing PEMs. It may be that consensus will be reached 20 years from now, but the concerns over part and supplier variation are not likely to change.

The continuous quality endeavor exerted by best-in-class IC manufacturers has resulted in another technological breakthrough that further removes PEM moisture susceptibility. Because of the high demand on smaller SMT versus the through-hole (i.e., DIP) packages, these suppliers have qualified their high-demand PEMs via the JEDEC standard (JESD22-A112 level 1) to achieve the highest moisture-robust level. This package qualification improves device robustness against moisture intrusion and thus eliminates any dry-pack storage needs. PEM suppliers guarantee all level-1 devices have unlimited floor life before assembly as long as they were stored under 30°C and 90-percent relative humidity. This level-1 qualification has demonstrated that today's PEMs, even with minimal plastic compound coating (smaller SMT packages), are "assembly-friendly" and extremely moisture-robust during long-term storage. This moisture-robust PEM initiative, that is pursued by best-in-class suppliers with the prime motivation of customer satisfaction and market competitiveness, is a classic example of today's BCPs.

6.1.2 Today's Market Realities and Trends

Today's military IC market accounts for less than 1 percent of the total IC market—and it is shrinking. Military stakeholders must realize their insignificant market presence. The lack of market influence leads to high "long-term availability" risk of the military components (i.e., ICs). For this reason, DoD instituted a commercialization thrust a few years ago to nourish a viable alternative. Because of this military market reality, military ICs no longer have the advantage over the commercial ICs (PEMs) for product obsolescence concern. Recent trends also show that the numbers of military IC manufacturers are diminishing.

In the area of system and assembly designs, the trend of using smaller, lighter and lower-power ICs is continuing. Many applications, such as the F-16 avionics electronics boxes, can take advantage of the space, weight, and thermal reduction scheme through effective use of the commercial IC offerings. Meanwhile, the design trend of 5-volt CMOS ICs has substantially declined from well over 95 percent in 1990 to about 35 percent in 1996, and is likely be below 20 percent in the year 2000.[7] Whereas, the designs of 3V and lower ICs are in an upward trend and are expected to exceed the 5-volt IC production beginning in 1997. This will have a significant impact on the existing military systems, since all the IC usage has been the 5-volt-type technology. However, it also created a redesign opportunity for the military systems to take advantage of the thermal benefits presented by these low-power consumption ICs.

6.1.3 IC Inequality

All military stakeholders should be aware that "not all parts (dies) and suppliers are equal. The inequality is primarily driven by the supplier's quality orientation, design expertise and manufacturing process capability.

Such variations can be minimized through a costly component screening process (i.e., Mil-Std-883s) or implementation of a proactive quality control process (i.e., 6-Sigma) via effective teaming with the selected BCP suppliers. This section proposes the latter choice.

All standard (non-custom) ICs (both PEM and military) may not have the same die under the same device type. In reality, these dies can be sorted based on pre-selected parameters (i.e., precision/speed), limits and temperatures into different product grades for the target market segments. The sorting usually occurs at the wafer probe and at the packaged level during the final electrical testing.

When an IC design is validated through statistical characterization of critical electrical parameters, it formulates the true capability of the IC. Such capability can be either distorted by variation within the manufacturing process or enhanced as a result of design and process improvements. Unless all possible variations are known and controlled effectively, it is unlikely that all dies are equal in terms of capability and robustness.

In today's commercial IC market, high C_{pk} (stable 6-Sigma process) and high yields equate to supplier profitability because more good dies per wafer are produced and less support overhead is required. To achieve this high-yield and high-C_{pk} IC, a period of learning and improvement of that particular IC technology is needed. The outcome could vary depending on the supplier's priority, expertise, and effectiveness of their design/process changes. Because of this time-lag characteristic of the quality demeanor of BCP suppliers, the technology and quality matured PEMs are more likely to be environmentally robust (i.e., extended temperatures).

6.2 PART AND SUPPLIER IDENTIFICATION

The part and supplier identification step is intended to identify applicable parts, and potential suppliers and distributors for final selection. This should be an ongoing discipline to research and compile applicable data on part availability and ranking of these suppliers or distributors. The applicable parts list can be derived from the needs of existing and anticipated military programs. Data should consist of a specific product type and grades (i.e., package, speed/precision and temperatures), lead-time, known dates of obsolescence, unit price, and minimum buy quantity. The supplier's engineering (factory) contact needs to be identified at this time for the possible technical inquiries, whether parts are being procured directly or through distribution.

With the baseline knowledge acquired from the previous framework step, the overall effectiveness of completing this identification process is likely to improve. The ability to leverage existing military supplier databases and supplier relationships adds a substantial value to the transformation process of PEM implementation.

PEMs have different parametric (i.e., speed grade A, B) and temperature (commercial, industrial, and military) grades, packages, and specific functional limits. It is important to identify each of these availabilities for the baseline comparison (i.e., performance and cost tradeoffs) among the potential suppliers. The supplier's ranking can be assessed through past performance records (e.g., cost, quality, teaming, on-time delivery, etc.) and a fact-gathering visit. Unless an OEM has developed a prior working relationship with the BCP suppliers, PEM purchasing is likely to go through distribution. The distributor can be a valuable ally for the procurement of low-volume and standard PEMs.

6.3 EVALUATION AND SELECTION OF PEMS AND SUPPLIERS

This is a critical step for the PEM implementation process. In a sense, this is a foundation building stage where the actual PEM implementation takes form. All baseline data on parts and suppliers are finalized at this step for near-term procurement needs and most importantly, positioning for the long-term teaming with the viable suppliers. Effective engineering decisions and supplier management insights are vital at this framework stage to assess and validate the application's "realistic" needs and PEM's "true" capabilities (i.e., design, reliability, and quality) as well as cost-risk tradeoffs.

6.3.1 Understand Application Needs

An important lesson that one can learn from today's innovative BCP is to step-out from the traditionally rigid military thinking by a "what-if" demeanor. The following excerpts were the notes taken from the recent Defense Manufacturing Conference (DMC '96):

- "If go by the book—we'll be dead in the trap . . .", cited by PEO for Surface Combatants/AEGIS Program, Naval Sea Systems Command, RADM George Huchting, USN during his opening speech on December 2.
- Mr. Terry Little, USAF's Program Director, Joint Air-to-Surface Standoff Missile Program Office, Aeronautical Systems Center, suggested that we should not treat requirements as sacred, and cost implication must be considered prior to any requirements (specifications) being made. The example he used was: "A college kid would tell you (as parent) all requirements he needs for his car, but would you just buy your kid that car without knowing what you can or cannot afford?"
- Mr. Little cited a 50-percent cost reduction on the JASSM program that was a direct result of today's affordability focus, and indicated that we must change the way to buy and interact with OEMs and suppliers. He was very pleased with Lockheed-Martin's aggressive, proactive, and innovative approach to improve the JDAM affordability via the adaptation of the low-cost commercial practices. Accordingly, Lockheed-Martin has effectively incorporated a change in the Actuator's torque requirement to reduce the JDAM kit cost. Such an idea was initiated by an Actuator supplier who indicated that they could drive lower cost through the use of industrial-grade components if the torque specification was relaxed. Overall system saving is substantial based on numbers of JDAM kits which are to be produced.

It is quite apparent that DoD's top-tier management are all speaking in one-voice in assessing today's military priority. They have been managing the defense cut-back effectively by initiating ongoing dialogues with the industry plus creating a competitive business environment that fosters affordability and creativity. The challenge for them is in waiting for the seeds of the cultural change to sprout. In short, today's military stakeholders need to be innovative by continuously finding better ways to develop effective military systems at affordable (lowest) cost.

Excessive specifications or requirements can accelerate system costs. A cost-conscientious system design discipline is needed to remove the possible arbitrary and over-conservative specifications, thereby driving to optimum affordability in today's military systems. This section advocates the need for a realistic system application or specification baseline to be defined before the down-selection of subsystems or parts.

At the same time, a parallel component engineering effort is needed to assess the true capabilities of PEMs in terms of performance, quality and reliability for use in military systems. It is equally important to take advantage of new-and-improved PEM technologies (i.e., unlimited floor-storage life against moisture intrusion) and to avoid the possible "sunset" technologies (i.e., the 5-volt CMOS digital). Effective system application and component capability match are keys to delivery of reliable military systems at the lowest possible cost.

6.3.2 Evaluate Reliability Data

BCP suppliers track essential performance and quality data religiously and are willing to share the data with potential customers. Reliability data usually consist of device's environmental qualification test data by product family, package and device types. The overall PEM qualification process is relatively common and standardized among the commercial suppliers. Military standards (i.e., Mil-Std-883) are still in use to baseline the applicable qualification test procedures, such as op-life, temp cycle, and thermal shock. JEDEC standards are commonly used for the PEM-unique life testing, such as, temperature/humidity life (THB), HAST, autoclave, and Molding Compound's Unlimited floor life qualification tests. Military standards do not exist for the PEM-unique life testing.

Each potential PEM supplier's reliability data should be reviewed for adequacy and baseline comparison with other suppliers. It is necessary to mitigate total-cost risk with additional reliability tests if the supplier's standard life tests are insufficient. Contrary to some beliefs, commercial suppliers are approachable. Some BCP suppliers do offer special product flows with enhanced reliability focus (i.e., Burn-in) for a specific device. Additional burn-in could add reliability value to the ICs that possess a newer technology and therefore has insufficient op-life data from the related product families. However, additional testing must be evaluated carefully against its incremental reliability (i.e., reduction in infant-mortality failures) to the added component cost.

6.3.3 Evaluate PEM's Extended Temperature Capabilities

An effective approach to determine the performance capabilities of any IC are through statistical characterization of device parametric values at the selected environments (i.e., temperatures). This has been a customary process for the IC manufacturers to validate their IC designs. They often repeat this characterization process to assess new business opportunities that have special performance needs (i.e., extended temperatures). Characterization is usually done by randomly selecting the dies from three different wafer runs, and then assembling them into packaged devices in quantities varying from 150 to 450 parts. These ICs are later electrically tested to generate characterization and yield data to validate the design capabilities. Although the IC pricing and specifications are derived from the IC design capabilities, other factors such as marketing strategies and competition can affect such decisions. Case in point, the new high-tech ICs that rushed into the market because of market influence are likely to be less specification robust than those have gone through months of quality improvement in design and manufacturing.

As discussed previously, the IC's design capabilities can be distorted when their true distribution is subdivided into different grades by the suppliers. It is always a good practice to select the most application-robust and cost-effective PEM when choices are available (i.e., I grade versus C grade). In some cases, suppliers do offer the "M" grade PEMs that guarantee the traditional military temperature limit (-55 to +125°C) at a higher cost. The electrical characterization of PEMs is essential for extended temperature applications when that temperature-range is beyond the supplier's specifications. It is critical to initiate the learning process with the BCP suppliers to understand parametric and temperature relationship, their design expertise and manufacturing/process

capabilities, and quality orientations. In many cases, suppliers do maintain the characterization data on PEMs at the extended military-temperature or a selected temperature-range for the automobile-market (i.e., -40 to +125°C). It is feasible to obtain characterization data if the previously stated "what-if" demeanor is properly applied (e.g., it is not proper to ask the supplier's marketer).

Through the evaluation of characterization data, a better risk assessment can be made when a system's critical parametric careabouts are compared side-by-side with the optimal characteristics of the device. In other words, there will not be a system risk if a don't-care parameter fails only at extended temperatures. This section also emphasizes that one cannot effectively evaluate the PEM's "true" capabilities (i.e., extended temperature) based on the specification alone. Effective supplier communication and teaming are the path for success. Could it be the appropriation of the "what-if" demeanor to unlock the mystery of the PEM capability?

6.3.4 Evaluate Lot-to-Lot Consistency (Quality)

Demonstration of the PEM capabilities is just the beginning in the framework of part and supplier selection. Further evaluations of a supplier's 6-Sigma quality process and a high level of collaboration are essential. Capability is simply a process potential and does not equate to quality (i.e., 6 Sigma C_{pk} quality). Progress in supplier teaming via the prior framework stages should enhance one's effectiveness to gain access and to evaluate this lot-to-lot quality focus. In a sense, such a proactive 6-Sigma quality initiative is a relatively new phenomenon in the traditional military IC's quality procurement practices where inspection and audit are the primary focus. This is a military OEM version of a "culture change" challenge as it was profoundly stated by the DoD for the paradigm shift toward BCP. Realizing this challenge, military OEMs need to be equally proactive and to foster this 6-Sigma quality focus in supplier teaming. The ability to leverage BCP supplier's 6-Sigma processes throughout their PEM manufacturing flow minimizes the lot-to-lot variation risk and thus optimizes the PEM usage. From a BCP perspective, this self-motivated quality endeavor, being undertaken by the responsive OEMs, becomes their competitive advantage in developing synergy with the BCP suppliers to ensure product reliability and affordability.

As stated in previous sections, dies (ICs) are commonly probed at the wafer stage in room temperature and sorted for different subsequent process flow. This is intended to optimize the final product yield in various grades based on the capacity demands and design constraints. This is a good data point for C_{pk} monitoring and assessment of the die's process consistency against the characterized electrical capabilities of the circuit. Usually, there is less guardbanding at the front-end (wafer) versus the back-end (packaged) with the intent of maximizing the throughputs of the dies. However, it still can be an excellent gauge with regard to assessing the lot-to-lot PEM variations. Most importantly, such C_{pk} data is usually not proprietary and can be shared with the customers. Again, effective communication with the suppliers is a vital process for selecting the key C_{pk} parameters and limits, and to implement the monitoring process. Via the advocated "what-if" analogy, successes in gaining collaboration from the BCP suppliers can be achieved with the prescribed "aggressive-proactive-innovative" demeanor without exclusively relying on the premise of "big volume and dollars."

Supplier's final electrical three-temperature average out-going quality (AOQ) data per product family and device type is another key quality checkpoint for PEM and supplier selections. Data consists of PEM failure rates in term of PPM (parts per million devices tested) representing the quality level of parts through supplier's outgoing electrical tests. Inspection data on PEM package- and mechanical-related failures are also available if needed. Most of the meaningful and non-proprietary PEM data is available for sharing, and the "relationship" and "hierarchy of need" (a proposed human psychological profile) will ultimately dictate such supplier's

collaboration capacity. The timely evaluation of the suppliers' lot-to-lot quality data enables OEMs to risk-assess the PEM reliability effectively before the assembly without additional screening.

Product yield will always be proprietary information, because of its direct implication to the firm's cost structure, profit margin, and competitive propensity. It is feasible for a supplier to increase the product yield by relaxing the specified test conditions/limits, instead of increasing the robustness of the part. While this could be a common business practice for a specific niche IC market, OEMs must possess the "inequality" awareness for parts and supplier's selection as it has been addressed in previous framework steps.

The preferred BCP scenario for the PEM implementation framework, suggested a BCP supplier would focuses on the mass IC market and continuously perfect their PEM design capabilities and assembly processes. As the result of these long-term marketing insights and quality demeanor, these PEMs are much more robust in terms of performance and reliability and positioned to gain market dominance. To cope with these BCP objectives, responsible suppliers implemented various incentive programs to foster this quality orientation and to motivate their engineers to innovate product and process improvement by aggressive goals on high yields.

As a result, these BCP suppliers established a culture that promotes design and process changes as the means to perfect the environmental robustness and process stability of their PEMs. A "culture change" is in order considering that military OEMs are traditionally concerned by any supplier changes. Subsequently, many PEMs underwent various re-characterization processes even at the extended temperatures to validate their enhanced capabilities and effectiveness to meet the expanded market segment needs.

Guardbanding has been an effective commercial practice used by the IC suppliers to reduce the numbers and cost of electrical tests for high-volume and process-matured PEMs. It refers to the tightening of the test specifications of one test (i.e., room-temperature) to correlate with the results of other tests (i.e., cold and hot temperatures). This guardbanding and correlation approach can be used to assess the lot-to-lot consistency of PEMs at an extended temperature-range (i.e., the requirement is between the I and M temperature grades). In the event that the guardbanding cannot be established, OEMs should consider the electrical sampling of the PEMs at the extended temperatures to ensure the quality of each PEM lot before assembly. If at all possible, OEMs should work with the BCP suppliers and take advantage of their existing special flow for conducting the tests. OEMs can also implement the sampling tests through a third party or possible internal test facility as an option to assess the extended temperature capability of each incoming lot. Ultimately, OEMs must assess the cost of the sampling tests versus cost and probability of a PEM failure at a system level.

6.4 LONG-TERM SUPPLIER TEAMING

The validation of PEM capabilities for the intended system (military) application, brings the PEM implementation process to its final step. Completion of this stage enables OEMs to master the PEM implementation process that optimizes the utilization of the cost-effective and reliable PEMs from BCP suppliers and thus achieves the ultimate military system affordability. This long-term supplier teaming can become a competitive advantage to ensure standard quality and enhanced capability without additional screening, and timely notification of product obsolescence.

To know "your" supplier is to know that supplier's unique strengths, weaknesses, opportunities, and threats (SWOT) relative to their products, technologies, market, and quality orientations. This SWOT analysis enables OEMs to formulate effective and innovative strategies to conduct effective communication and to gain optimum

teaming with each of the potentially "unique" BCP suppliers. It also provides valuable insights to OEMs to adapt (to fit in) the supplier's mass market BCP that is responsible for ongoing improvement on performance capabilities (robustness) and lot-to-lot quality (consistency).

Effective supplier communication is a building block for long-term supplier teaming. To seek out the right supplier contacts to initiate the PEM implementation process is a challenge event in today's changing paradigm, but it is necessary. In essence, this teaming stage is an extension of all supplier communications from the previous stages within the framework, and therefore all initial communications should be directed toward this long-term supplier teaming focus.

In today's limited military budget and "humble" market presence, the ability to team with the best-in-class IC suppliers and to leverage their quality demeanor constitutes a skillful discipline in today's IC procurement practices. A new marketing paradigm for "buyer to solicit seller" is likely in order. OEMs should leverage the existing or prior supplier relationship to gain the overall supplier collaboration. Moreover, OEMs should also centralize their IC purchasing power (volume) to enhance the strategic teaming process with the BCP suppliers.

SECTION 7
CONCLUSIONS

7.1 PEM ASSESSMENTS

Modern PEMs manufactured by BCP suppliers possess the capability of supporting the Military-temperature avionics systems requirements. Extended temperature evaluations demonstrated these parts can operate reliably at temperatures exceeding their specifications. This capability can be attributed in part to the robust design process used by the supplier, the maturity of the technology associated with the evaluated parts, and the relaxed Mil-Spec parametric limits as the parts are derated from the commercial temperature parametric limits.

The 2-percent failure rate of PEMs in the extended temperature range provided correlation to a previous DS&E evaluation of PEM extended temperature performance. Assessment of the failures could be attributed to one part type and one supplier. This data demonstrates that proper use of PEMs requires: (1) in-depth knowledge of the part under consideration and (2), knowledge of supplier capabilities. Areas of concern include part technology, the maturity of the technology, and the supplier process controls and capabilities.

The Sonobuoy PEM assessment provided an opportunity to evaluate parts that had been assembled and stored for 10 to 12 years in various environments and assess their performance both within specification limits and at extended temperatures. The parts evaluated can best be described as mature both from a technology and production standpoint. This demonstrates that these parts normally exhibit robust performance and utilize mature processes that provide consistently high quality parts.

The CCA evaluation provided an assessment of the capability of PEMs to withstand normal assembly processes and to operate at the extended temperature range required of the Mil-Spec parts. The conclusions may be colored somewhat by the robustness of the CCA design and other performance attributes, which were not assessed: however, in this case, there is the potential to reduce the cost significantly by using PEMs without having an adverse affect on the CCA reliability.

7.2 F-16 AVIONICS APPLICATION

The data gathered on the aircraft environmental environments provided an opportunity to evaluate typical operational conditions versus specified conditions. The results indicate that most of the specified conditions are worst case and there is merit in designing to a more typical or nominal condition resulting from the cost reductions possible through PEMs. The study determined nominal conditions of -40 to +105°C were applicable to most avionics equipment on the F-16 Block 50 aircraft configuration.

7.3 GENERAL

This study focused on gathering data through objective assessments of PEM performance at the extended temperature range required in military applications. The results indicate clearly that PEMs are capable of this performance. In addition, other process and design-related considerations were addressed. PEM implementation in avionics designs necessitates that an OEM become concerned with how best to ensure consistent part quality in the absence of Mil-Spec controls. These concerns were addressed through the PEM implementation framework process. This becomes a very critical part of the design consideration as OEMs move toward commercial processes in lieu of dependence on Mil-Spec controls. This process provides a framework for assessing the risk associated with the selection of any part or supplier.

SECTION 8
LESSONS LEARNED

8.1 SUPPLIER TEAMING IS POSSIBLE

While it is logical to assume that the PEM suppliers would give little or no attention to today's "humble" military customers, we found there are exceptions. Mass-market-focused suppliers like to expand their business with their robust PEMs. It depends on "who" and "how" you initiate the communication. The "do-it-my-way" attitude would not get you very far in a conversation. Use the "what-if" demeanor suggested in the PEM implementation framework and be selective in choosing the supplier contact for initiating the communication.

8.2 AVOID CONSERVATISM

Like suppliers and OEMs, none are equal. Some are best-in-class (BCP) and willing take calculated risks to turn challenges into opportunities. Case in point, some suppliers intentionally commit their resources to improve the PEM yields by improving the part's application robustness to be successful in all possible market segments. Others have found reasons to limit themselves and remain in a few selected markets. Today's new military businesses are higher-risk because of acquisition reforms, which have placed a heightened level of responsibility and risk on the OEMs. Military OEMs could accept the DoD challenge as an opportunity to dominate this new military market by providing affordable systems through effective risk management. Or, like some suppliers, OEMs can simply remain entrenched in the comfort zone of a niche market that offers minimal risk. The risk-avoidance demeanor of a supplier or an OEM does not fit the need for the long-term DoD business teaming.

8.3 CENTRAL SUPPLIER/PEM DATABASE IS NOT TODAY'S COST-EFFECTIVE ENDEAVOR

In a fast-paced and high-volume commercial world that demands changes to keep pace with the market realities, the resources required to maintain up-to-date part-counts with corresponding supplier and part test data are insurmountable. This data would make the PEM implementation process a much simpler task. With the funding issue aside, in the midst of the "culture change" at DoD, the subject task is nearly impossible.

8.4 ASSESSMENT OF THE AVIONICS' TEMPERATURE APPLICATIONS IS A PROCESS—NOT A SINGLE EVENT

The LM F-16 Block 50 avionics temperature data suggests that an opportunity for PEM implementation is feasible for nominal operating conditions. This data baselines an optimal temperature range for PEM implementation of -40 to + 105°C. Risk management begins at the part-selection stage to optimize the system validation success. Lockheed-Martin's system design experience suggests that different designs, configurations, and locations could alter the existing temperature-range baseline. Therefore, the temperature-related application assessment should be an ongoing process to validate the most realistic temperature requirement.

SECTION 9
RECOMMENDATIONS

In light of the recent years of continuous research and debate over the extended capability and reliability of PEMs for military applications, today's military stakeholders do not all share the same conclusion. At one end of the spectrum, the stakeholders need more reliability validation data before PEM implementation. While at the other end of the spectrum, OEMs need an effective PEM implementation process to mitigate the total cost risk that results from the possible lot-to-lot variations of the PEM shipments. Through the research process of this AMSUCP study, it is recognized that these needs can be satisfied with effective execution of the proposed program highlighted below.

9.1 FOLLOW-ON CASE STUDIES FOR PEM IMPLEMENTATION

- Case-Study I: Validate the framework through the distribution of the proposed teaming process with additional suppliers. Perform the extended temperature and reliability (moisture) evaluations on specific PEMs from these suppliers. Define specific 6-Sigma parameters and process levels to correlate out-going quality of the final packaged device. Develop a 6-Sigma monitoring system that is supportable by these selected suppliers. Identify specific design considerations for the OEMs before the part and supplier selections.
- Case-Study II: Validate the framework process and its effectiveness through an existing military program. Through execution of framework-proposed steps and guidelines, compare the reliability and cost of the new PEM design assemblies to the existing military baseline. Perform CCA-level extended temperature and environmental evaluations to assess the applicable capability and reliability further.
- Case-Study III: Upon the successful validation of Case-study I and II, this case-study will compile all lessons learned and data into a shared database or final report. The database will include the relevant supplier quality, reliability, and PEM performance data, and documentation of all applicable test data of the results of extended temperature and moisture-reliability evaluations (if any).

9.2 FOLLOW-ON CCA BENCHMARK EVALUATIONS ON MOISTURE RELIABILITY

Leverage the available AMSUCP's six build-up and environmentally tested CCAs (three PEMs and three Mil-ICs) and CCA performance verification capabilities to assess the relative moisture-life of the selected PEMs and Mil-ICs. Through THB and HAST, along with additional contamination process and moisture-life modeling, the relative moisture reliability will be demonstrated through this benchmarking process. Comparative reliability assessment could add significant value to capture the essence of the moisture-life analysis without mingling with the technical details.

9.3 TECHNICAL ASSESSMENT OF TODAY'S PEM MOISTURE LIFE EVALUATIONS

Review current studies (various experiments) and technologies (i.e., scanning acoustic microscopy), and their key components (i.e., activation energy) that are significant to attain total realization of PEM moisture robustness for various military applications (i.e., long-term dormant storage). This study entails an evaluation process to validate the effectiveness of up-to-date PEM moisture testing and prediction methodology. Another moisture-life evaluation will be performed to assess various suppliers and PEM capabilities using the recommended (validated) PEM assessment process.

9.4 ASSESSMENT OF "OTHER" COMMERCIAL PART CAPABILITIES FOR MILITARY APPLICATIONS

Assess the military applicability for the utilization of today's non-IC commercial electronics components (i.e., transistors, capacitor, resistors, etc.). This study will explore the possible advantages and disadvantages in terms of affordability, reliability, and availability for various military applications.

REFERENCES

(1) Electronics Buyer's News, December 02, 1996, Section: Passives. "Resistors: Steady As They Go", by Diane Norman.

(2) **Non-mil microcircuit**
Any microcircuit that supplied compliant to the internal control requirements of a microcircuit suppliers instead of military specification requirements. Non-mil microcircuits are typically documented by a supplier's datasheet/databook, and to a much lesser degree to an OEM's control specification (if significant volumes are procured).

Clarification of the terms "Commercial IC" and "non-mil microcircuit"
The military market often refers to non-mil microcircuits as commercial ICs. The term "commercial IC" is not sufficiently descriptive since the term is often used within the semiconductor industry to refer to a components operating temperature range or availability within the market. Commercial and industrial ICs are contained within the broader term of non-mil microcircuits.

(3) Plastic Encapsulated Microcircuit (PEM), also referred to as a "plastic IC." Plastic packages are the most common package style used for microcircuits.

A large majority of non-mil microcircuits are offered only in plastic packages. Not all non-mil microcircuits use plastic encapsulation (i.e., high power devices use ceramic of metal packages to improve thermal properties of the device).
Plastic microcircuits are not common for military-grade microcircuits. However, the existing military specifications for microcircuits do allow suppliers to supply military-grade PEMs.

(4) **Military compliant microcircuit**
A microcircuit that is supplied as compliant with Mil-Std-883, Mil-Prf-38535, or Mil-Prf-38534. Although the "military specifications" (Mil-Prf-38534 and Mil-Prf-38535) have been converted to "performance based specifications," beyond the traditional military manufacturers of microcircuits, the microcircuit industry has not embraced these specifications. These components are documented frequently via standardized microcircuit drawings (SMDs) and to a lesser degree to an OEM's control specifications. For military systems, the microcircuit components used have traditionally been military compliant (Mil-Std-883, Mil-Prf-38535, Mil-Prf-35534). Included within these specifications are new allowances for packaging materials—both hermetic, as well as non-hermetic (such as plastic)—and allowances for temperature ranges other than the traditionally accepted extreme, referred to as the "military temperature range" (-55°C to +125°C).

(5) E. Hakim, et al, "A Case Study of the Field Reliability of Dormant Plastic Encapsulated Microcircuits"—Preliminary release.

(6) Sun Man Tam, TI DS&E. "Demonstrate Reliability of Plastic-Encapsulated Microcircuits for Missile Applications", IEEE Trans. Reliability, Vol 44, 1995 March, pp 8-13.

(7) "A Semiconductor Overview", by TACTech, Inc., July 1996—Source: 1996 Integrated Circuit Engineering Inc.